ERUPTIVE ROCKS

S. J. SHAND

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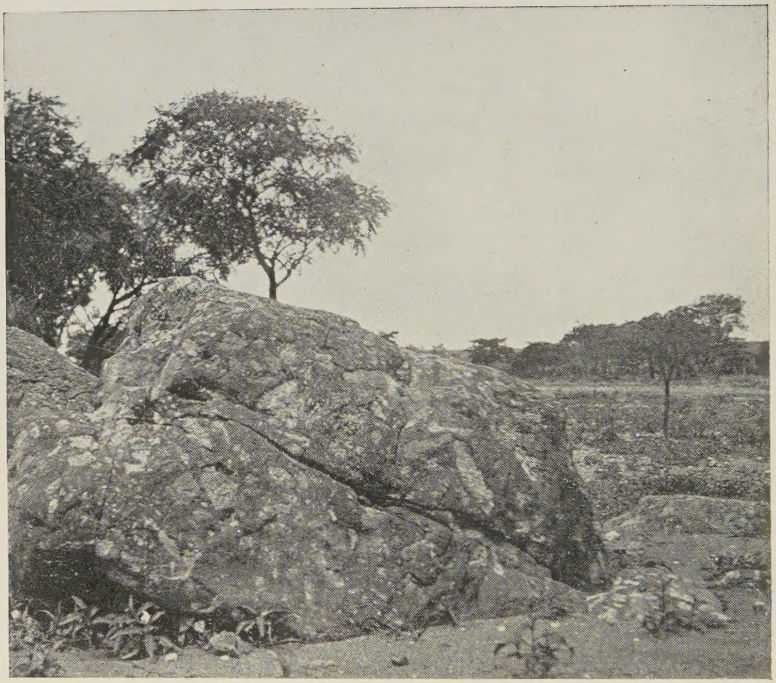
ERUPTIVE ROCKS



The outcrop of a dolerite dyke which cuts granite near Bulawayo, Southern Rhodesia. The dolerite is crowded with fragments of quartz and felspar, probably derived from a pegmatite reef in the granite. (By courtesy of Mr. A. Frost, Bulawayo.)

[*Frontispiece.*

ERUPTIVE ROCKS

THEIR GENESIS, COMPOSITION, CLASSIFICATION, AND THEIR RELATION TO ORE-DEPOSITS

WITH

A CHAPTER ON METEORITES

BY

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I dedicate this work to my father, who taught me to love books, and my mother, who gave me a logical mind.

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First, of course, there's the things you don't know; then there's the things you do know but can't understand; then there's the things you do understand but which don't matter. Saving your presence, sir, there's a heap of understanding to be done before you're anything but a fool.

—*A. E. COPPARD, "Simple Simon."*

PREFACE.

This book is the outcome of three insistent wishes which have occupied the writer's mind ever since he came under the spell of the study of eruptive rocks.

There was first the wish to clean up the jungle of rock names. The method of petrographers in giving names, as a great American geologist has pointed out, has been to give an independent name to every rock that is a little different from any one seen before, without reference to any plan; a practice which has led to the multiplication of rock names to a degree far in excess of the needs of the science. The consequence is not merely that one cannot see the wood for the trees, but rather that one cannot see the trees for the brushwood. This state of affairs pleases nobody, yet many would rather perpetuate it than face the revolution of names and terms that a new method involves. Thus a reformer is between the devil and the deep sea, for if he adapts a new system to existing names, with their connotations, it will be still-born, and if he introduces a new nomenclature, it will be stoned to death by those who feel that the burden of rock names is already greater than they can bear. But something must be done; somebody must make a move; and that is the first reason for this book.

A second wish arose out of the first. It was to make the results and conclusions of petrology intelligible to matter-of-fact people like physicists and chemists, who like to do their thinking in quantitative terms, and who are apt to listen with indifference to the assertions of " affinity " and " consanguinity " that underlie so many petrographic contentions. Petrology needs all the help that chemistry can give it; but before they look for help, petrographers must learn to express their problems in terms that a chemist can understand. That means that they must pay more attention than has been their habit to the chemical resemblances and differences between rocks, and above all, that they must give

a quantitative meaning to the terms they use. To make a step in this direction is the second reason for this book.

Thirdly, it has been the writer's wish to bring theory and practice together, and to save petrology from the reproach of being an academic study, of little use in life. Petrology and mineralogy owe much to mining, and should give something in return. A rational system of petrology, that is neither too vague nor too difficult to understand, is a gift that the miner and all who are interested in the mineral industries would not fail to appreciate. On the other hand, the petrologist who turns his attention to the study of ore-deposits will find it a rare source of information and inspiration. To show that the miner and the petrologist have need of each other's help is the third reason for this book.

A difficulty, which everybody who attempts the reform of petrography must face, is that very few petrographers have troubled to describe their rocks in quantitative terms. This is particularly true of English, French, and German writers. Even in America, the writers who supply numerical data are far fewer than those who say " a little " of this mineral, " not much " of the next, and " a good deal " of the other—expressions which are no longer used even in cookery-books. Such descriptions were useless for the writer's purpose, and this meant that a vast quantity of material had to be rejected in the preparation of this book. For instance, from the eighty odd pages which Rosenbusch gives to the description of andesites, in his *Mikroskopische Physiographie,* it is impossible to discover the precise composition (either mineralogical or chemical) of any single one of these rocks. The consequence is, that one had to pick up examples suitable for quotation wherever one could find them, and often a very well-known rock had to be left out of account, and a much less familiar occurrence used in its place, simply because the former had not been described quantitatively. It is unfortunately true, as Dr. H. S. Washington has remarked, that many rocks are so " well-known " that they have never been properly studied or described. So if the work of W. C. Brögger, L. V. Pirsson, R. A. Daly and H. S. Washington seems to be given undue prominence in the

descriptive chapters, the reason is just that few petrologists have done more work than they, and no others have made such consistent use of quantitative methods of description.

In the matter of terminology and nomenclature, the writer has gone his own way, guided by the general principles that names should be as few as possible, that the simplest terms are the best, and that when an English term can be used without obscurity, it should be preferred to a Latin or Greek one. In view of the repugnance which a new set of names would arouse, he has used only well-known names of wide implication. These have been redefined, but it will be found that the new definition contains the kernel of the old one in every case. To define afresh all the varietal names that are in use would be an impossible task, even if it were desirable or legitimate. Better to let them all die out; and to introduce new ones from time to time, as the need for further subdivision is felt; so the names will arise out of the classification, as they ought to do, instead of the classification growing round the names.

The writer gladly records his appreciation of the helpful spirit in which Mr. G. H. Freeman (Messrs. T. Murby & Co.) has co-operated with him in the production of this volume.

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CHAPTER I.

ERUPTIVE OR IGNEOUS ROCKS.

Petrology begins with the examination, description and classification of the kinds of rock that form what we call "the crust of the earth," but it does not end there. The philosophical aim of the study, which is too often lost sight of, is to discover the chemical composition of the matter beneath the crust, to throw light upon the physical conditions that prevail there, and to investigate the physical and chemical changes that take place during the formation of rocks. Physicists may weigh the earth, geodecists find its form and volume, astronomers record its movements, and seismologists study its elasticity, while philosophical geologists build theories of the earth upon these data; but the petrographer alone has tangible evidence of what lies beneath the crust. It is presented to him by his own planet in the form of plugs and tongues of eruptive rock that have come up from the depths, and by mineral veins. It is presented to him by other members of the solar system in the form of meteorites. No theory of the earth or of the solar system can stand, that disregards the evidence of eruptive rocks and meteorites. And since the problem of the earth's composition, with which that of its genesis is bound up, surely overshadows all other non-organic problems, so petrology, as the science which contributes most directly to the solution of that problem, may claim a place in the front rank of the natural sciences.

The practical aim of the study is also an ambitious one. Mineralogical and petrological research shows ever more and more clearly that an intimate connection exists between eruptive rocks and mineral deposits of commercial importance. It is already possible to lay down some general principles in the matter, connecting certain minerals and certain special types of ore-deposition with particular groups of eruptive rocks. It is evident that well established generalisations of this kind may be very valuable in the hands of a miner or prospector who has a sufficient knowledge of petrology to apply them correctly. There is much to be learned before the search for mineral deposits can be placed upon a sound

scientific basis; but this and nothing less should be the aim of petrology on the practical side.

The science of petrology is generally considered to embrace the study of all rocks, whether eruptive or sedimentary, and whether affected by metamorphism or not. It is well to realise that this arrangement is dictated solely by convenience. The sedimentary rocks, having been formed by the disintegration of older eruptive rocks, have about as much in common with the latter as sawdust has with a living tree; consequently the principles of study and classification which are suited to the two classes of rocks are quite distinct. Biology long ago found it necessary for its health and progress to split itself up into the two sciences of zoology and botany, which have their roots in common ground, but otherwise live their lives independently; and for the same reason there is need for petrology to separate its two branches which are concerned with eruptive and with sedimentary rocks respectively, permitting them to meet only in the common ground of metamorphism.

In this volume the eruptive rocks alone are considered, together with the mineral deposits to which they give rise and the meteorites to which they are nearly related.

We may open the discussion with the remark that the adjectives " igneous " and " eruptive " are currently applied to rocks as if they were synonymous. Are all eruptive rocks igneous, using that word in the fullest sense which is warranted by its derivation from *ignis*, fire? It is true that in the case of lava discharged by an active volcano, we have the evidence of our senses to assure us of its " fiery " or molten origin. But this evidence is lacking in respect of other rocks which we are used to consider igneous. No one ever saw a molten granite or syenite, because these rocks are formed deep down in the crust of the earth, and they only become accessible to our observation after ages of denudation. What justification is there for putting deep-seated rocks like granite and syenite in the same category with the really " igneous " lavas? This is the very question that agitated the Neptunists and Vulcanists of last century, and as the matter lies at the root of the science of petrology, we shall devote this chapter to its consideration.

The proof that granite and other deep-seated crystalline rocks were fluid at one time in their history is afforded by the manner of their occurrence in the earth's crust. Wherever the junction between a mass of granite and any other rock is exposed to view,

it is found to be a very irregular surface, often approaching the vertical position. In the case of the Marysville granite mass in Montana, the upper surface of the rock was thoroughly explored in mining operations, and Joseph Barrell reports that it was "extremely irregular, steep or vertical surfaces alternating with flat surfaces, giving the whole a rudely pyramidal form with a somewhat step-like surface, from which project dykes, sheets and chimneys." (*Fig.* 1.)

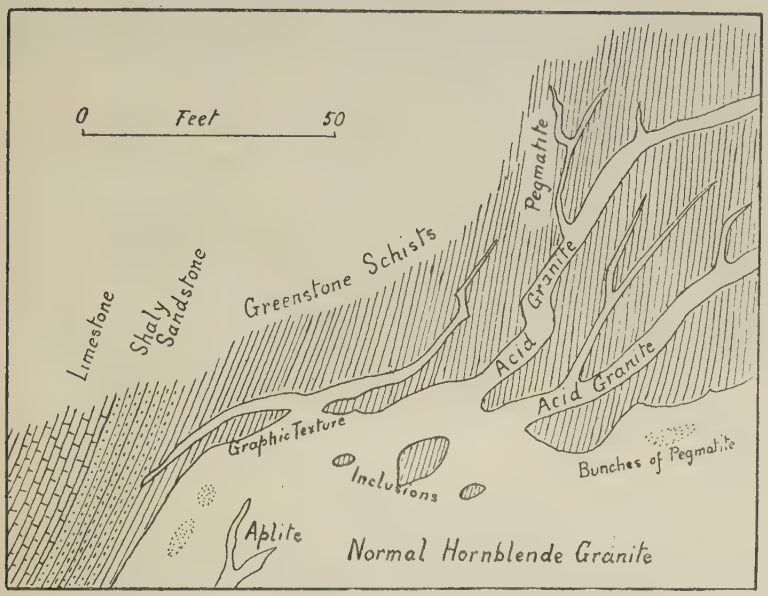

FIG. 1. Part of the margin of the Boulder batholith, Montana. (After P. Billingsley.)

In the neighbourhood of such a junction, the granite is often seen to enclose blocks of the surrounding rocks, which have been detached from the walls and transported towards the heart of the granite mass. If a series of such enclosed blocks is examined, from the junction inwards, one readily convinces oneself that the foreign rock was actually being corroded, disintegrated, and incorporated in the granitic magma, and that the action was only stopped by the freezing of the mass. From such a junction, too, the granite commonly sends offshoots in among the country rocks, either in the form of sheets which follow the bedding planes of the country rocks, or of dykes which cut across these planes, or of

thin veins that penetrate the most minute cracks. (*Fig.* 2.) Or, instead of the regular injection of magma into fissures, the country rock may present the appearance of having soaked up the magma much as a sponge soaks up water, so that the product is charged with felspar and other minerals apparently derived from the magma. The evidence of fluidity on the part of the granite magma, which is presented by contact phenomena such as these, seems to be incontrovertible.

It was by observations of this kind that the Vulcanists of last century were convinced of the "igneous" origin of coarse-grained rocks like granite and syenite. Glen Tilt, in Scotland, is

FIG. 2. Junction of granodiorite (left) with Cretaceous beds; Castle Peak, British Columbia. (After R. A. Daly.) Scale, one inch to 185 feet.

classic ground to the student of petrology, for it was there that James Hutton found the evidence which confirmed him in his view of the igneous nature of these rocks. The description of the evidence given by two fervent Huttonians, Lord Webb Seymour and Professor Playfair, is still worth reading, if only for its bearing upon a historic controversy. Having observed fragments of limestone, gneiss and other rocks enclosed in the granite (or sienite, as they call it) of Glen Tilt, they write as follows:—

"The similarity of the stratified substances (*i.e.*, fragments of limestone, gneiss, etc.) lying in separate masses among the sienite, to those which compose the base of Ben y Gloe, and occupy a wide dis-

trict to the south and west, leaves no room for doubting that both are of the same formation. But if this be admitted, and likewise the common origin of the sienite in the main rock and in the veins, the inter-mixture of the stratified masses with the sienite remains to be accounted for, and the case seems to admit of only two hypotheses. One is, that after the sienite had assumed its present form, the stratified substances were deposited in the cavities of its surface. . . . The hypothesis which remains is, that the masses of gneiss, limestone, etc., are portions of strata once continuous, and lying conformably with those which form the base of Ben y Gloe; that these strata were bent and broken by some violent shock; and that the fluid, from which the sienite crystallised, was intruded among the fragments.

Admitting this as the most probable, the nature of that fluid comes immediately into question. It may be supposed to have been some unknown aqueous fluid, which held the substance of the sienite in solution, and deposited it by crystallisation. . . . But an objection to any idea of a crystalline deposition from an aqueous fluid, arises from the compactness of the rocks. . . . Had an aqueous solution deposited this substance among fragments, in some places so confusedly heaped, in others so closely fitted together, we might have expected to have found occasionally what so frequently occurs in a calc-tufa, a porous structure, and cavities, perhaps lined with crystals. On the contrary, in all these veins, however complex and minute, scarcely a single interstice appears unfilled. It is to heat then that we may with more probability ascribe the fluidity of the sienite."

Another classic locality for the study of the same question is Table Mountain, Cape Town. An account of the granite-slate contact on Table Mountain was furnished in the early years of last century by Captain Basil Hall, R.N., to Professor Playfair, who communicated the observations to the Royal Society of Edinburgh, in 1813, himself commenting on the matter as follows:—

"The penetration of the killas or grauwacky [now known as the Malmesbury slate] by veins from the mass of granite which it surrounds, proves that the killas, though the superior rock, is of older formation than the granite. The granite, therefore, is a mineral that has come up from below into the situation it now occupies, and is not one of which the materials have been deposited by the sea in any shape, either mechanical or chemical. It is a species, therefore, of subterraneous lava. . . .

I know not that we have ever before had an example which so directly ascertains the place which granite really occupies, in respect of the other parts of the mineral kingdom; it is one that from analogy might be expected to take place, and it is highly favourable to the opinion, that granite does not derive its origin from aqueous deposition. It seems, indeed, to be an *instantia crucis* with respect to the two theories concerning the formation of rocks."

The proof of fluidity, however, does not carry with it that of high temperature. It is true that no solvent is known which will dissolve and deposit appreciable quantities of quartz, felspar and mica at ordinary temperatures, yet many instances can be named

in which crystals of quartz and felspar have been formed in rocks without the aid of heat. Such are the veins and pockets of rock crystal which one often finds in sandstones and limestones. In certain cases, felspar and quartz have been formed in unconsolidated deposits on the ocean bottom, under circumstances which seem to preclude the operation of any higher temperature than that of sea water. In this matter, the operation of the factor of time is to be seen; for although silica and alumino-silicates are hardly appreciably soluble in water, yet the continuous circulation of water through the pores of a rock during long periods of time may permit the transportation of large quantities of these substances, particle by particle, and their deposition on the walls of a suitable fissure.

That water is actually present during the crystallisation of granite, and still more of vein-quartz, is abundantly proved. It has long been known that quartz crystals often contain drops of liquid, and gas bubbles, and the investigations of Brewster, Humphrey Davy, Hartley, and many later workers have shown that the liquid is just salt water. Although the cavities in which the fluid is found are generally very small, often no more than one ten-thousandth of an inch in diameter, yet their number may be so great that the specific gravity of the rock is appreciably reduced by them. The following calculation is due to A. A. Julien:—

> "In the quartz of Cornish granites the cavities sometimes make up at least five per cent. of its volume, and the water in them, on an average, about one per cent. of its volume, or four-tenths of one per cent of its weight. As the quartz grains in a granite or in gneiss rarely amount to less than fifty per cent. of the whole rock, it is probable that the liquid contents of such a granite commonly reach as much as one-fifth of one per cent.; *i.e.*, about four pounds of liquid to a ton of rock."

It is hardly possible to doubt that the water and the dissolved salt were actually present in the magma from which the quartz crystallised. Quartz crystals are almost devoid of cleavage, and except by way of cleavage planes or other cracks the liquid could not have got into the crystals after they were full grown. And if it could enter by way of minute cracks, it could escape by the same way; yet the contents of the cavities are sometimes found to be under pressure; indeed some of them contain, instead of water, liquid carbon dioxide, which at its critical temperature of 31° C. requires a pressure of 73 atmospheres to keep it liquid. Other minerals besides quartz show such enclosures, notably

topaz, and in general it is the minerals which were last to crystallise from the magma that are richest in fluid enclosures, indicating that the residual magma was progressively enriched with water and gas as crystallisation advanced.

An important investigation of the enclosures in the minerals of eruptive rocks was carried out by Henry Clifton Sorby, who was the inventor of the method of preparing thin sections of rocks for study under the microscope. His observations on the enclosures in crystals were among the first fruits of the new method of investigation. Sorby showed that in the minerals of granites the enclosures are mostly of liquid or gas; but that in lavas there are present similar cavities which contain *glass* instead of fluid. In some cases, owing to the glass having become minutely crystalline, the cavities contain an exceedingly fine-grained stony material. Between rocks which showed glass enclosures only, and others which showed liquid enclosures only, a connecting link was found in certain rocks which hold enclosures of both kinds; this condition Sorby observed in the " trachyte " of Ponza, and in some Cornish granites and granitic dykes. F. Zirkel afterwards recorded similar phenomena in leucite crystals, the same cavity sometimes holding both glass and liquid.

The main conclusions to which Sorby was led by his discoveries are given here, in his own words :—

" On the whole, then, the microscopical structure of the constituent minerals of granite is in every respect analogous to that of those formed at great depth and ejected by modern volcanoes, or that of the quartz in the trachyte of Ponza, as though granite had been formed under similar physical conditions, combining at once both igneous fusion, aqueous solution, and gaseous sublimation. The proof of the operation of water is quite as strong as that of heat; and in fact I must admit that in the case of coarse-grained, highly quartzose granites there is so very little evidence of igneous fusion, and such overwhelming proof of the action of water, that it is impossible to draw a line between them and those veins where, in all probability, mica, felspar, and quartz have been deposited from solution in water, without there being any definite, genuine igneous fusion like that in the case of furnace slags or erupted lavas. There is, therefore, in the microscopical structures, a most complete and gradual passage from granite to simple quartz veins."

" With respect, then, to minerals and rocks formed at a high temperature, my chief conclusions are as follows. At one end of the chain are erupted lavas, indicating as perfect and complete fusion as the slags of furnaces, and at the other end are simple quartz veins having a structure precisely analogous to that of the crystals deposited from water. Between these there is every connecting link, and the central link is granite."

The evidence, derived from the study of the liquids enclosed in

crystals, that water actually played a part in the magma from which granite consolidated, is confirmed by many field observations. Near any great granite intrusion it nearly always happens that dykes and veins of the eruptive rock are thrust out into the country rock, often to considerable distances. Even commoner than these dykes are seams of pure white quartz, which on account of their composition and structure have always been assumed to be of aqueous origin. But it is sometimes possible to follow a single dyke from its point of origin on the edge of the granite mass to a position where, by gradual loss of felspar and mica, it passes without any lack of continuity into a quartz vein. In illustration of this highly important observation we select the description by C. R. van Hise of the granite dykes of the Black Hills in South Dakota.

"The core rock is a great batholith of granite, 7 miles broad and 11 miles long. . . . From the central mass great quartz-felspar dikes radiate. In passing away from the core the dikes become smaller and have a less typical form. At the same time the material assumes the appearance which we ordinarily denominate as pegmatitic. These veins might be considered true igneous injections. Passing still further away, the pegmatitic masses begin to have vein-like characters—that is, there is a rough concentration of the material in different layers, parallel to the walls. In going still further away a true banded vein structure is found. In passing yet further away, felspar becomes less and less important in the veins and the quartz more abundant, until remote from the granite the impregnating material is mainly quartz. . . .

If one examined only the outer zone, in which the quartz impregnations occur, he would not doubt that they were ordinary deposits from water: if he examined the masses of the inner zone, adjacent to the great granite mass, he would not doubt that they were true igneous injections; but passing back and forth from the one zone to the other, he observes that there is every gradation between the two."

Similar observations have been made in many parts of the world, but we can allow ourselves only one more quotation, which we take from the memoir by F. D. Adams and A. E. Barlow on the geology of the Haliburton and Bancroft areas in Ontario:—

"The pegmatites are prevailingly rich in felspar, this constituent largely predominating over the quartz. In places, however, this latter constituent becomes more abundant, especially at the extremity of the dike where it becomes narrow. In fact, cases can be observed where the felspar is represented only by a few individuals here and there, and the dike develops into a mass of quartz. Such an occurrence, if seen alone, would undoubtedly be considered as a quartz vein, but in this area no genetic distinction can be drawn between the two occurrences. The quartz veins, in these cases at least, are merely a form or phase of the pegmatite dikes."

The reason why we cannot consider such quartz veins to be

igneous intrusions is just that the melting point of pure silica is about 1700° C., a temperature high enough to have melted the country rocks in which the veins are found; yet these rocks show no sign of having been heated.

Loosely combined water (so-called water of crystallisation) is actually present in some of the rarer constituents of pegmatite. O. Stützer describes a specimen of drusy pegmatite from the Striegau granite, Saxony, now preserved in the Freiberg museum, where the zeolite stilbite is present as the final product of consolidation. This mineral holds four molecules of water of crystallisation. J. Lehmann mentions a specimen of Baveno granite, in the Bonn museum, in which quartz and felspar crystals lining a drusy cavity are coated with scaly iron-mica and crystals of laumontite, a zeolite with two molecules of water of crystallisation.

But even lava—most typical of " igneous " rocks—furnishes evidence of the presence of water in the magma from which it was derived. Chemical analyses of pitchstone, a glassy rock occurring in dykes and flows, show from five to ten per cent. of water. It is possible to regard this water as a recent addition to the rock, but there is no necessity for such an assumption, since it has been shown that it is possible to prepare artificial glasses containing even larger proportions of water than pitchstone holds. G. W. Morey has heated potassium silicate glasses along with water in steel bombs, and has obtained homogeneous glasses containing as much as twenty per cent. of water. Sir Charles Parsons performed the experiment of melting olivine in presence of water, under a pressure of ten tons to the square inch. When the pressure was suddenly removed, an artificial pumice was formed in consequence of the escape of the water that had been absorbed by the melt. Zünckel and Hempel have also found that water and carbonic acid are readily dissolved by molten silicates.

Many lavas carry minerals, such as mica or zeolites, into whose composition water or its elements enter. The more siliceous lavas hold biotite, from which, at a moderate temperature, some five per cent. of water can be extracted. Less siliceous lavas often exhibit cavities which are lined with beautiful crystals of the zeolites, a group of minerals which earned their name by virtue of the abundance of water which they give off when heated. It is often assumed that zeolites are formed after the lava is cold, by the agency of ground water, but this is not necessarily so.

David Forbes produced before the Chemical Society in the year 1868 a specimen of the lava ejected by Mount Etna during the eruption of 1865; this specimen, taken while the lava was still flowing, contained crystals of stilbite, a zeolite holding seventeen per cent. of water of crystallisation.

Thus even lava, while it is fluid, holds water (or the elements of water) in solution; and it is this water, escaping from the surface of the lava, that gives rise to the clouds of steam that so often accompany volcanic eruptions.

We see, then, that granite is in no way sharply distinguished from a lava such as rhyolite, for:—

(1) in chemical composition granite and rhyolite may be identical;

(2) the same minerals that appear in granite reappear in rhyolite;

(3) there is a perfect gradation, as regards texture, from completely glassy lavas such as obsidian, through rhyolite and granite porphyry, to completely crystalline granite;

(4) the evidence of initial fluidity is as clear in the one case as in the other; and we have seen that there is a continuous passage from rocks in which the presence of glass is proof of melting, to others, such as quartz veins, whose constituents we must suppose to have crystallised from solution in water.

It must follow, then, that we are fully justified in placing the granites and other plutonic rocks in the same category with lavas, and in a different one from sedimentary rocks. But it by no means follows, as Sorby's remarks indicate, that we are justified in applying the name "igneous rock" to granite and lava alike. The lavas are igneous rocks: so too are many of the rocks which constitute dykes and sills; this is proved by the presence of glass in them. Also, since some lavas are completely crystalline, one may argue that, so far as texture is concerned, the more coarse-grained plutonic rocks may equally well have been formed from igneous melts. But in the case of some plutonic rocks, and particularly granite, the evidence for the agency of water as a contributory cause of fluidity is just as strong as the evidence for fusion.

Sorby tried to ascertain the actual freezing temperatures of some granites by observing the temperature at which the liquids,

enclosed in the cavities of quartz crystals, completely filled these cavities. In his own words:—

"When crystals are formed at an elevated temperature, evidence of it is afforded by the contraction of the fluids enclosed in the cavities giving rise to a vacuity. . . . Since, of course, the amount of the contraction of the fluid depends upon the height of the temperature from which it has cooled, the relative size of the vacuity must indicate how much the temperature at which the crystals were formed was above that at which they are examined, in the same manner as the sinking of the mercury in a self-registering thermometer shows the difference in the temperature."

By the application of this principle, Sorby obtained results ranging from 89°, for some granites, to 356° for a quartz-bearing lava. More recent work shows that Sorby's estimates were almost certainly too low, but that many of the coarser granite pegmatites completed their crystallisation below 575°, and most of the quartz-bearing rocks probably below 700°. The truth is, however, that none of the methods yet employed for settling the question is quite beyond criticism, and all that can be said with positiveness is that the granites have been formed at temperatures decidedly lower than the freezing temperature of any known lava.

J. Clifton Ward, who applied Sorby's methods to the granites of the Lake District of England, came to the conclusion that eruptive magma may exist in two states, which he describes as follows:—

"(1) That state in which igneous fusion is the most important or conspicuous element. This is seen in the case of lava flowing from a volcanic vent.

(2) A state of aqueo-igneous fusion, occurring at a much greater depth than the last, and reaching only a dull red heat (*i.e.*, about 400°) as a maximum. In this state we have every reason to suppose the granite magma to be, which may now be solidifying . . . beneath our feet."

The reliability of Sorby's ingenious method was questioned by S. Allport, who pointed out that if the cavities were originally completely filled with liquid, and the bubbles were formed solely by contraction, then the ratio of size of cavity to size of bubble ought to be constant in any one part of the rock. But Allport found that this ratio was not constant, either in the same rock or even in the same crystals.

The temperature of flowing lava has been variously estimated at 1000° to 1200° C. and even higher. The latest and most reliable measurements made by T. A. Jaggar at Kilauea show that such extremely high temperatures are only realised at the surface of the liquid, where escaping gas is in active combustion; but that the temperature of the lava below the surface may be

750° to 850° C. At this relatively low temperature it is likely that crystallisation of the lava has already begun, for well-formed crystals of augite and leucite have been observed in perfectly fluid lava at Mount Vesuvius.

It follows, then, that we should not be justified in calling granite an igneous rock, if by that name we mean a rock "formed by the agency of fire," or by anhydrous fusion, which is the original connotation of the name. If the term "igneous" conveys to its hearers the idea that the rocks to which it is applied were once in the state of anhydrous melts, with temperatures of 1000° or more, then it is better to throw it over in favour of an alternative adjective such as eruptive or magmatic, which conveys the idea of fluidity without any assertion or implication about temperature.

The foregoing summary has indicated that the system of placing the "igneous rocks" in one category, in opposition to the "aqueous" mineral veins, requires modification. Some mineral veins are closely akin to eruptive rocks, and ought not to be separated from them. Some eruptive rocks have more kinship with the contents of mineral veins than they have with lavas. A truer view of the relation of the eruptive rocks to one another, and to a certain class of mineral veins, is given by a continuous linear classification such as the following:—

Conditions.	*Products.*
Temperature of consolidation high (Above 700°?) Water sparingly present	Extrusive rocks (lavas).
Temperature of consolidation high to moderate (700°—600°?) Water present in notable quantity	Most intrusive rocks.
Temperature of consolidation moderate (600°—375°?) Water plays important part in composition of magma	Coarse-grained rocks with much alkali-felspar and quartz or nepheline. Some eruptive ore-bodies.
Temperature of consolidation low (Below 375°) Water essential to formation	Quartz veins and other mineral deposits.

There are no sharp lines of division between these groups; thus the lavas are connected by dyke-rocks of every conceivable

grain and texture with the coarse-grained intrusive rocks; the latter pass into pegmatitic facies; and pegmatites, as we have seen, often pass directly into simple quartz veins. But since both custom and convenience demand that we should make some distinction between the " igneous " and the " aqueous " ends of the series, we may suggest a convention to the effect that all crystalline rock masses and veins which contain much quartz of prismatic or fibrous habit, and little or no felspar, shall be excluded from the category of eruptive rocks.

REFERENCES.

Adams, F. D. and Barlow, A. E.—Canada, Geol. Survey, Mem. 6, 1910.
Allport, S.—Quart. Jour. Geol. Soc., 1876, *414*.
Billingsley, P.—Trans. Amer. Inst. Min. Eng., 1915.
Daly, R. A.—Proc. Nat. Acad. Sci., 1917, *659*.
Hall, B.—Trans. Roy. Soc. Edinburgh, 1815, *277*.
Hartley, W. N.—Jour. Chem. Soc., 1876, *137*.
Jaggar, T. A.—Amer. Jour. Sci., 1917, *161*.
Julien, A. A.—Jour. New York Micro. Soc., 1885, *140*.
Lehmann J.—Die Entstehung der altkryst. Schiefergesteine. Bonn, 1884.
Morey, G. W.—Jour. Amer. Chem. Soc., 1914, *215*.
Parsons, C.—Nature, 1920, *709*.
Sorby, H. C.—Quart. Jour. Geol. Soc., 1858, *453*.
Stützer, O.—Zeitschr. prakt. Geol., 1909, *131*.
Van Hise, C. R.—U.S. Geol. Survey, 16 Ann. Rep., *581*.
Ward, J. C.—Quart. Jour. Geol. Soc., 1875, *568*.
Webb-Seymour—Trans. Roy. Soc. Edinburgh, 1815, *303*.
Zůnckel, R. and Hempel, W. –Zeitschr. Vulkanologie, 1917, *256*.
Zirkel, F.—Zeit. deutsch. geol. Gesellschaft, 1868, *132*.
do. —Lehrbuch der Petrographie, vol. 1, 1893, *166-190*.

CHAPTER II.

THE FIXED CONSTITUENTS OF ERUPTIVE ROCKS.

A REMARKABLE feature of the eruptive rocks is the small number of mineral species of which they are composed. Out of the hundreds of silicates and aluminosilicates that are known, or that are theoretically possible, only a very few are common constituents of eruptive rocks; and among these the felspars, pyroxenes, amphiboles and micas, together with quartz, predominate enormously over all others. For this reason the investigation of an eruptive rock usually requires the determination of a few silicates only, together with certain oxides, sulphides, phosphates and titanates which may be present in trifling quantities.

This apparent simplicity is more than neutralised by the very complex constitution of many rock-forming silicates, and by the fact that most of them, as they appear in rocks, are not simple species, but *solid solutions* with a wide range of composition. The nature of solid solution is most conveniently illustrated by reference to simple salts which are soluble in water.

The sulphates of magnesium, zinc, nickel and cobalt are isomorphous, that is, they have very similar chemical properties, and, in addition, they form crystals of nearly identical habit and angles, each holding seven molecules of water of crystallisation. If a crystal of one of these salts—say magnesium sulphate—is introduced into a saturated solution of another—say the cobalt salt—it will grow as freely as if it were in its own mother-liquor, but the new layers will be formed of pink cobalt sulphate. If the crystal is removed after a time and placed in a saturated solution of the nickel salt, the pink layer will be succeeded by a layer of green nickel sulphate, and so on. But if all four sulphates are present in one solution, then the crystals which separate out on cooling are homogeneous, and each contains all four sulphates in the proportions in which they are present in the liquid. It is thus possible, by varying the composition of the solution, to prepare crystals which shall contain any desired proportions of zinc, magnesium, nickel and cobalt; and if one were given such a crystal,

it would be impossible, without chemical analysis, to ascertain its precise composition.

Such crystals, whose composition varies with that of their mother-liquor, are solid solutions; and the property of forming solid solutions and layered crystals, or overgrowths, is characteristic of all isomorphous substances. Among the rock-forming minerals, cases of isomorphism and solid solution are so numerous and important that they have led to the grouping of these minerals into large "natural families," the names of which are usually better known than those of the simple species which make them up. We must now pay some attention to the chemical characters of the principal families of rock-forming minerals.

The Felspar Family contains four distinct species, in nature, and several series of solid solutions. The species are:—

$KAlSi_3O_8$ (orthoclase or microcline)
$NaAlSi_3O_8$ (albite)
$CaAl_2Si_2O_8$ (anorthite)
$BaAl_2Si_2O_8$ (celsian)

Orthoclase and albite form a series of solid solutions which are called soda-orthoclase or potash-albite, according to which component preponderates. Practically all the "orthoclase" which we identify in rocks is soda-orthoclase, containing an average amount of fifteen per cent. of albite, according to H. L. Alling's determinations. Under changed physical conditions, it is believed that these solid solutions sometimes split up into their components, or "come unmixed," so giving rise to the minute intergrowths of orthoclase and albite which we know as perthite and microperthite. Dittler and Köhler have shown that microperthite, when heated for a long time at 1000°, reverts to homogeneous soda-orthoclase.

Albite and anorthite give a series of solid solutions to which the group-name of "plagioclase" is applied. Oligoclase, andesine, labradorite and bytownite are names given to those sections of the plagioclase series which hold from 10 to 30, 30 to 50, 50 to 70, and 70 to 90 per cent. of anorthite respectively. The crystals of plagioclase in rocks are sometimes homogeneous and sometimes layered, like the magnesium sulphate crystals described above. In the latter case, the cores of the crystals are generally rich in anorthite and the layers are progressively richer in albite towards the outside.

Solid solutions of orthoclase with anorthite are not found in

nature, but a complete series of them has been prepared in the laboratory by A. L. Day. The orthoclase-celsian series is of rare occurrence in nature.

Ternary solid solutions, containing orthoclase, albite and anorthite, are of frequent occurrence; indeed the members of the binary series that we have been discussing nearly always hold a little of the third component, but either so little lime is present that the solution does not differ greatly from soda-orthoclase, or else so little potash that the product is scarcely distinguishable from a binary plagioclase. The names anorthoclase and potash-oligoclase are applied to the more definitely ternary solid solutions. The disinclination (if one may call it so) of potash-felspar to associate with much lime-felspar in nature is one of the most significant facts of petrology.

The composition of any felspar is conveniently expressed by the use of Or, Ab, and An as shorthand symbols for the pure components; thus Ab_{32} An_{68} would be a plagioclase, falling in the labradorite section of the series; and Or_{26} Ab_{66} An_{8} is the composition of a possible anorthoclase.

The felspars have all been produced synthetically. Plagioclase with more than 20 per cent. of anorthite will crystallise from a simple melt of its constituents, but more sodic plagioclase, like pure albite and orthoclase, can only be induced to crystallise by the addition of a flux. The melting point of pure anorthite is 1550° (N. L. Bowen); that of albite about 1200° (Day and Allen). Orthoclase dissociates above 1170° into leucite and silica (Bowen and Morey).

The Metasilicate Family contains the simple species, molecular compounds, and solid solutions that are named below. A new complication is introduced, in this family, by the tendency of each species to change its crystal habit in response to changes of temperature, pressure, or concentration in the magma. The critical values of the factors which determine the transformation are not known; but one may say roughly that at the higher magmatic temperatures, and under more nearly anhydrous conditions, the *pyroxene* habit, which is characterised by a cleavage angle of about 90°, is favoured; while at lower temperatures, and in the more hydrous magmas, the *amphibole* habit, with a cleavage angle of about 55°, is assumed.

The simplest chemical formulæ that can be written for the pyroxenes and amphiboles represent them as solid solutions of the

types $R''SiO_3$ and $R'R'''(SiO_3)_2$. F. W. Clarke has advanced reasons for regarding them as mixtures of polysilicates with orthosilicates. It is clear that:—

$$R_2Si_3O_8 + R_2SiO_4 = 4\ RSiO_3$$

so the empirical formula derived from the analysis of such a mixture as Clarke assumes, would represent it as a metasilicate. It is commonly assumed that the molecule of an amphibole is more complex than that of the corresponding pyroxene, but Clarke points out that the pyroxenes have the greater density and ought therefore to have the larger molecules. It must be left to the future to determine the actual constitution of these minerals; for our purpose the simple metasilicate formula is adequate. The simple pyroxenes and amphiboles are as follows:—

	Empirical formula.	*Pyroxene.*	*Amphibole.*
1.	$MgSiO_3$	Enstatite	—
2.	$FeSiO_3$	—	Grünerite
3.	$CaSiO_3$	Wollastonite	—
4.	$MnSiO_3$	Rhodonite	—
5.	$MgAl_2SiO_6$	Tschermak's silicate	
6.	$NaAl(SiO_3)_2$	Jadeite	Glaucophane
7.	$NaFe(SiO_3)_2$	Ægirine	Riebeckite

There are also titanium-bearing and lithium-bearing species.

The principal molecular compounds are:—

8.	$CaMg(SiO_3)_2$	Diopside	—
9.	$CaFe(SiO_3)_2$	Hedenbergite	—
10.	$CaMg_3(SiO_3)_4$	—	Tremolite

The solid solution series may be condensed as follows:—

Series A. The *ortho-pyroxenes* (for which the names bronzite and hypersthene are also used) are solid solutions of 1 and 2, crystallising with orthorhombic symmetry.

Series B. The *clino-pyroxenes* are monoclinic in crystallisation. They fall into four sub-groups.

(a) The *diopside* series contains molecules 8 and 9.

(b) The *augite* series consists principally of 8 and 9, together with 5. A titanium-bearing molecule is sometimes present in addition, giving the variety "titan-augite."

(c) The *enstatite-augite* series has 1 and 5 as its characteristic molecules, and

(d) The *soda-diopside* series contains No. 7 along with Nos. 8 and 9, forming what is sometimes called "ægirine-augite." Less commonly the jadeite molecule (No. 6) is present instead of ægirine.

Series C. *Ortho-amphiboles* are only found in metamorphic rocks.

Series D. *Clino-amphiboles* fall into three sub-groups.

(a) The *actinolite* series, consisting of tremolite and its iron-bearing variety, actinolite. These correspond to the diopside series in B.

(b) The *hornblende* series, corresponding to the augite series in B.

(c) The *soda-amphiboles*, including glaucophane, riebeckite, crocidolite, and a number of ill-defined varieties, such as arfvedsonite, hastingsite, barkevikite and catophorite, which are intermediate in composition between common hornblende and the true soda-amphiboles.

When one considers all the possibilities in the way of solid solution in this family, it becomes evident that the "augite" and the "hornblende" which the petrographer identifies in his rock sections are far indeed from being minerals of definite composition. The following table exhibits the wide range of composition observed in specimens of augite and hornblende from various eruptive rocks.

	Augite.	*Hornblende.*
SiO_2	44.55 to 53.63	38.41 to 54.89
Al_2O_3	2.82 ,, 9.15	1.50 ,, 17.58
Fe_2O_3	0.27 ,, 7.95	*nil* ,, 19.11
FeO	1.47 ,, 15.08	0.94 ,, 22.22
MgO	10.05 ,, 17.05	2.54 ,, 19.50
CaO	15.98 ,, 23.46	9.55 ,, 14.32
Na_2O	*nil* ,, 1.47	*nil* ,, 3.18
K_2O	*nil* ,, 1.19	*nil* ,, 2.18
TiO_2	*nil* ,, 4.28	*nil* ,, 10.31
H_2O	*nil*	*nil* ,, 2.79

Both ortho- and clino-pyroxenes crystallise readily from dry melts in the laboratory, and from furnace slags. Amphiboles are never formed under such conditions; but K. Von Chrustchoff obtained amphibole crystals by heating silica, alumina, and various hydroxides to 550° C. in presence of water; and Allen and

Clement prepared a magnesian amphibole under similar conditions at 375°—475°.

The melting points of some of the pyroxenes are as follows:— Enstatite dissociates at 1557° into forsterite and glass (Bowen and Andersen); hypersthene melts about 1190° (C. Doelter); pure diopside at 1391° (N. L. Bowen); and augite generally in the neighbourhood of 1200° (Doelter). Hornblende dissociates before its melting point is reached, giving augite and magnetite or augite and olivine (Doelter).

The Mica Family. The molecular constitution of the members of this family is not fully understood. F. W. Clarke regards all the micas as substitution products of the theoretical aluminium silicates $Al_4(SiO_4)_3$ and $Al_4(Si_3O_8)_3$, as in the following table:—

Muscovite, $Al_3(SiO_4)_3KH_2$ with some $Al_3(Si_3O_8)_3KH_2$
Biotite, $Al_2(SiO_4)_3Mg_2KH$
Phlogopite, $Al(SiO_4)_3Mg_3KH_2$
Paragonite, $Al_3(SiO_4)_3NaH_2$
Lepidolite, $Al_3(SiO_4)_3HKLi$ with $Al(Si_3O_8)_3K_3Li_3(AlF_2)_3$
Zinnwaldite, $Al_2(SiO_4)_3Fe_2KH$ with $Al(Si_3O_8)_3K_3Li_3(AlF_2)_3$

Part of the aluminium in biotite may be replaced by ferric iron, giving the variety called lepidomelane, or by chromium or vanadium, and some of the magnesium is nearly always replaced by ferrous iron or manganese. Titanium is present in many micas, but it is not known whether it replaces silicon or aluminium. Fluorine is seldom completely absent, and it amounts to seven per cent. or more in the lithia micas. The range of composition that is exhibited by rock-forming biotite appears in the following table:—

SiO_2	from	32.49	to	40.81
Al_2O_3		12.34		18.81
Fe_2O_3		0.72		20.15
FeO		4.88		25.13
MgO		1.34		23.91
Na_2O		0.15		1.55
K_2O		6.50		9.59
H_2O		1.37		5.30
TiO_2		*nil*		4.73
F		*nil*		1.61

Both muscovite and biotite have been produced in the laboratory by the use of various fluxes containing fluorine. The

presence of water is also an indispensable condition. The micas dissociate when heated under atmospheric pressure; from biotite, C. Doelter obtained augite, olivine, spinel and scapolite or melilite, while he got leucite and glass by melting muscovite. W. Vernadsky, no doubt under different conditions, found that mica broke down into corundum and sillimanite.

The Tourmaline Family. Many elaborate formulæ have been proposed to express the constitution of this complex family, but there is little reason for preferring one of them to another. The old formula of Rammelsberg has the advantage of simplicity. It represents all tourmalines as mixtures of salts of the acid H_6SiO_5, for example

$$x\ R'_6\ SiO_5 + y\ R''_3SiO_5 + z\ R'''_2\ SiO_5$$

where $R' = Na, K, Li$; $R'' = Mg, Fe, Ca$; $R''' = Al, B, Cr$.

The first of these molecules predominates in the alkali-tourmalines, while the second is almost completely absent. Common tourmaline holds chiefly the second and third molecules, with either magnesia or iron predominating. Tourmaline is the only common rock-forming mineral that contains boron. Fluorine is a minor component of most varieties of tourmaline, and a variable amount of water or hydroxyl is always present. The composition of common tourmaline is consequently quite as indefinite as that of hornblende or biotite, as the following analytical data will show:—

SiO_2	34.63 to	41.16
B_2O_3	9	11
Al_2O_3	25.29	44.05
Fe_2O_3	*nil*	6.6
Cr_2O_3	*nil*	10.8
FeO	*nil*	14.4
MgO	*nil*	14.9
CaO	*nil*	5.1
Na_2O	*nil*	3.59
K_2O	*nil*	2.17
Li_2O	*nil*	1.73
H_2O	*nil*	4.61
F	*nil*	1.19

Tourmaline does not crystallise from anhydrous melts and it has never been observed in slag. No synthesis of tourmaline has been effected.

The Silica Group. Three forms of silica exist in apparent stability in eruptive rocks, apart from chalcedony and other imperfectly crystallised varieties of low-temperature formation. Quartz is the stable form, under atmospheric pressure, at all temperatures up to 870° C.; tridymite between 870° and 1470°; and cristobalite from 1470° to its melting point about 1710°. With slow cooling, and in presence of fluxes which ensure free movement of the molecules, both tridymite and cristobalite transform into quartz when the temperature falls below 870°; hence in deep-seated eruptive rocks only quartz is found. But the transformation is sluggish, and either rapid cooling or high viscosity of the melt may delay it to such an extent that one or other of the high-temperature forms is perpetuated under conditions that are theoretically unfavourable to it. Thus one can understand why tridymite and cristobalite are often found in lavas, but never in deep-seated rocks. C. N. Fenner writes that:—

"The presence of cristobalite or tridymite in a rock does not necessarily imply that at the time of formation of these minerals the temperature was above the respective inversion points (1470° and 870°). Any set of conditions which will bring together quantities of ungrouped SiO_2 molecules in such a manner as to favor their rapid assemblage in definite groupings without giving time for perfect equilibrium to be established (as in the reactions of vapors); or which will suddenly bring a system in which equilibrium prevails into new conditions, at the same time introducing obstacles to the establishment of a new equilibrium (as in the sudden chilling of a melt), will favor the deposition of unstable forms."

Quartz itself is known in two forms which differ slightly in appearance and crystallographic character, and have a transformation point at 575°. The high-temperature form, or β-quartz, is the one usually found in eruptive rocks, but some coarse granites and pegmatites hold α-quartz, which is the only kind found in quartz veins.

Any form of silica can be converted into cristobalite by heating nearly to the melting point, without the aid of a flux. Both tridymite and cristobalite make their appearance in the silica bricks which are used for lining furnaces. To obtain quartz crystals in the laboratory, the agency of water or a flux is generally required, but Morey and Bowen have obtained quartz bipyramids from an anhydrous sodium silicate melt at 750°.

The Olivine Family. So far as concerns eruptive rocks, this is principally a group of simple orthosilicates of magnesia and iron. A lime-bearing olivine, monticellite, is of very rare occur-

rence in eruptive rocks. Some olivine has titania replacing part of the silica.

The simple olivines are:—

Forsterite,	Mg_2SiO_4
Fayalite,	Fe_2SiO_4
Monticellite,	$MgCaSiO_4$
Lime-olivine,	Ca_2SiO_4

The common olivine of gabbros and basalts is a solid solution of forsterite and fayalite, the observed range of composition being roughly as follows:—

SiO_2	36 to	42%
TiO_2	*nil*	6
FeO	5	49
MgO	16	51
CaO	*nil*	1.4
MnO	*nil*	1.5

Olivine crystallises readily from magnesium silicate melts which lack the silica necessary for the formation of enstatite. If plenty of silica is present, only enstatite is formed. O. Andersen and N. L. Bowen have shown that the forsterite-silica association is only stable above 1557° C.; below that temperature enstatite takes the place of forsterite. Forsterite melts at 1890° (N. L. Bowen) and fayalite at 1255°; common olivine about 1400° (Doelter and J. H. L. Vogt).

The Nepheline Family contains the rather uncommon species nepheline, and the very rare kaliophilite and eucryptite. Within this family we may also place the sodalite group of minerals, and cancrinite, all of which are most simply regarded as addition products of nepheline. The empirical formula for nepheline is $NaAlSiO_4$; but F. W. Clarke prefers to regard this mineral as a derivative of the aluminium silicate $Al_4(SiO_4)_3$, thus indicating its relationship to muscovite, which is one of the commonest decomposition products of nepheline. Adopting Clarke's view, the chief members of this family are as follow:—

Nepheline,	$Al_3(SiO_4)_3Na_3$
Kaliophilite,	$Al_3(SiO_4)_3K_3$
Sodalite,	$Al_2(SiO_4)_3Na_4(AlCl)$
Hauyne,	$Al_2(SiO_4)_3Na_2Ca(AlSO_4Na)$
Nosean,	$Al_2(SiO_4)_3Na_4(AlSO_4Na)$
Cancrinite,	$Al_2(SiO_4)_3Na_4H(AlCO_3)$

It will be noticed that the last four formulæ can also be written in a more easily remembered form as 3Nepheline + NaCl, 3Nepheline + $CaSO_4$, 3Nepheline + Na_2SO_4, and 3Nepheline + $NaHCO_3$ respectively.

Pure kaliophilite is a rare mineral, but most natural "nepheline" is a solid solution of kaliophilite in nepheline, having roughly five times as much soda as potash. Since analyses of nepheline often show more silica than the above formula requires, F. W. Clarke assumes that the molecule $NaAlSi_3O_8$ (or perhaps rather $Na_3Al_3(Si_3O_8)_3$) is also taken into solution. In addition, N. L. Bowen has proved that synthetic nepheline can take anorthite into solid solution, up to a maximum of 35 per cent. It is thus possible that in nepheline-plagioclase rocks the former mineral may hold some of the latter in solution; yet Bowen's assertion that natural nepheline holds more than ten per cent. of plagioclase, goes beyond the facts. The best analyses of clean, carefully separated nepheline, such as that of York River, Ontario, which was studied by J. B. Harrington, show only a trace of lime, and even that trace may be due to microscopic enclosures of other minerals. P. Chirwinsky has found, in sixteen analyses of nepheline, an average amount of only 0.43 per cent. of lime. Forty-four analyses are quoted by C. Doelter in his Handbuch der Mineralchemie, and the average content of lime is only 0.7 per cent.; this would give about $3\frac{1}{2}$ per cent. of anorthite if the lime were entirely present in that form, which is quite uncertain.

The following range of composition has been observed in nepheline:—

SiO_2	41.9	to	45.1
Al_2O_3	29.4	,,	34.5
Na_2O	14.4	,,	18.6
K_2O	0.9	,,	7.1
CaO	*nil*	,,	2.0 (impurity?)

Nepheline has been synthetised by fusing its constituents together, with the addition of sodium tungstate as a flux. It has also been produced by various hydrothermal reactions; G. Friedel obtained it by treating muscovite with a ten per cent. solution of sodium hydroxide at 280° C. Sodalite and nosean were formed by the same process, when sodium chloride or sodium sulphate was added. Cancrinite was obtained by J. Lemberg, by heating

kaolin in a solution of sodium carbonate. Kaliophilite was prepared by G. W. Morey, by heating potassium aluminate and silicate with water at 600°, under a pressure of about 1,000 atmospheres.

Nepheline transforms at 1248° into a cubic modification called carnegieite, which, on cooling, does not revert to nepheline, but develops a complicated lamellar twinning like that of plagioclase (Bowen and Greig).

Leucite and Analcime. The empirical formula of leucite is $KAlSi_2O_6$, but F. W. Clarke shows that its chemical behaviour is more easily explained if it is regarded as a mixed salt containing both orthosilicate and trisilicate molecules, as $K_4Al_4(SiO_4)_2(Si_3O_8)_2$. The formula of analcime must be similar to that of leucite, with soda in place of potash, and with water of crystallisation added; it is generally written $NaAlSi_2O_6 + H_2O$. J. Lemberg showed that leucite can be transformed into analcime, or analcime into leucite, by treatment with solutions of soda and potash salts respectively at 180°. In spite of this simple relationship, natural leucite contains very little soda, and natural analcime seldom more than a trace of potash. Leucite crystallises readily from dry fusion, but analcime requires the presence of water under pressure, and was prepared by A. de Schulten by heating alumina with a sodium silicate solution at 180°. Ferguson and Merwin find that the melting point of pure leucite is above that of platinum (1755°).

The Melilite Family. This group of minerals has been studied especially by W. T. Schaller and A. F. Buddington, who find them to be solid solutions of high complexity. Some of the simple molecules which compose the family are the following:—

1. Gehlenite	$2\ CaO,\ Al_2O_3,\ SiO_2$
2. Akermanite	$2\ CaO,\ MgO,\ 2\ SiO_2$
3. Sarcolite	$3\ CaO,\ Al_2O_3,\ 3\ SiO_2$
4. Soda-sarcolite	$3\ Na_2O,\ Al_2O_3,\ 3\ SiO_2$
5. Iron-sarcolite	$3\ CaO,\ Fe_2O_3,\ 3\ SiO_2$

Between 1 and 2 there is complete solid solution, and limited solution between 1 and 3 and between 2 and 3. Common melilite consists chiefly of 3, 2, and 5, with minor quantities of 4 and 1, but even with all these molecules it is not possible to express the

exact composition of every example of the mineral. Analyses of melilite show the following range of composition :—

SiO_2	38.3 to 44.7
Al_2O_3	6.4 ,, 12.0
Fe_2O_3	0.5 ,, 10.2
FeO	*nil* ,, 3.7
MgO	5.7 ,, 8 6
CaO	27.5 ,, 35.6
Na_2O	1.9 ,, 4.7
K_2O	0.3 ,, 1.5

Melilite crystallises easily from dry fusion of its constituents, and it is a common product in furnace slags. It melts at about 1050°, according to J. H. L. Vogt.

The Garnet Family includes a number of isomorphous species which conform to the empirical formula $R_3X_2(SiO_4)_3$, where R stands for magnesium, calcium, ferrous iron or manganese, and X for aluminium, ferric iron, titanium or chromium. Silicon may also be replaced to a limited extent by titanium. An artificial soda-garnet has been made, and soda has been detected in some varieties of garnet. Some of the simpler species are as follows :—

Grossularite	$Ca_3Al_2(SiO_4)_3$
Pyrope	$Mg_3Al_2(SiO_4)_3$
Spessartite	$Mn_3Al_2(SiO_4)_3$
Almandine	$Fe_3Al_2(SiO_4)_3$
Melanite (andradite)	$Ca_3Fe_2(SiO_4)_3$

Common garnets are solid solutions of two or three of these species at once. Most garnets do not recrystallise as such after melting, but break up into pyroxene, olivine, melilite, or anorthite; melanite is the only species of garnet which has been crystallised from a silicate melt. Manganese and lime garnets were prepared by A. Gorgeu, by heating pipeclay to redness, along with manganese chloride or calcium chloride, in a stream of water vapour.

The Epidote Family appears, from its empirical formula, to be closely related to the garnet family. The simple lime-epidote (zoisite) has the formula $Ca_2(AlOH)\,Al_2(SiO_4)_3$. Common epidote differs from this only by having part of the aluminium replaced by iron. In allanite, or cerium epidote, aluminium is partly replaced by cerium, lanthanum, and didymium. The range

of composition shown by rock-forming epidote and allanite appears below.

SiO_2	31.6	to 38.6
Al_2O_3	11.4	28.6
Fe_2O_3	1.6	13.3
$(Ce,Di,La,Y,Er)_2\ O_3$	*nil*	23.5
FeO	*nil*	13.6
CaO	9.4	25.1

Epidote has not been synthetised.

Oxides. The commonest of these is magnetite, Fe_3O_4, or FeO,Fe_2O_3. The ferrous iron in this formula is replaceable by magnesium or manganese, and the ferric iron by aluminium or chromium, giving a series of isomorphous compounds which are known collectively as spinel. Ferric iron is also replaceable to a considerable extent by titanium, giving titanomagnetite, which forms a connecting link between pure magnetite and the highly titaniferous ilmenite, $FeTiO_3$, or $(FeTi)_2O_3$.

Hematite, Fe_2O_3, is a scanty constituent of many eruptive rocks, and is perhaps in most cases an alteration product. The same remarks apply to rutile, TiO_2, and other oxides of titanium. Corundum, Al_2O_3 is an uncommon constituent of eruptive rocks, and its appearance, in certain cases at least, is due to solution of aluminous sediments by the magma.

Magnetite crystallises directly from silicate melts and furnace slags. Hematite is produced by the action of steam on iron salts at red heat; it is often observed in the slaggy parts of lava flows, where the iron silicates of the magma have been decomposed by steam. The spinels have been crystallised by various processes involving the use of fluxes. Corundum crystallises from dry silicate melts, and from direct fusion of alumina in the oxy-hydrogen blowpipe; it has also been obtained at temperatures as low as 400° by heating alumina with sodium hydroxide. The following melting-points are given by J. H. L. Vogt:—

Corundum	2050°
Chromite	1850°
Magnetite	1580°
Hematite	1565°
Ilmenite	1450°

Zircon and Zirconosilicates. The principal minerals which contain zirconium, in eruptive rocks, are:—

Zircon, $ZrSiO_4$.

Eucolite (eudialyte), which according to Clarke has the formula $Na_3Ca_3(SiO_4)_3\ ZrCl + Na_3Ca_3(Si_3O_8)_3\ ZrCl$.

Catapleiite, $Na_2Zr(SiO_3)_3 + 2H_2O$.

Also wöhlerite, rosenbuschite, lavenite, and others of doubtful composition. Zircon alone is of common occurrence, but eudialyte and others are important in certain classes of rocks. The melting point of zircon is about 2000° (C. Doelter).

Titanosilicates and Titanates. Many minerals have already been mentioned in which titanic acid replaces silicic acid to a limited extent. The following should be added:—

Sphene, $CaSiTiO_5$

Perovskite, $CaTiO_3$

Astrophyllite, $Fe_4Na_4Ti\ (SiO_4)_4$

Ænigmatite and rhönite are rare titanosilicates which are generally referred to the amphibole group.

Phosphates. In addition to apatite, $3\ Ca_3P_2O_8$, CaF_2, which is found in traces in nearly all eruptive rocks, it appears that xenotime, YPO_4, is not uncommon in granites and syenites, where it is often mistaken for zircon. Monazite, a phosphate of the cerium group of metals, occurs in some granites. W. Mackie has found it to be widely distributed in the granites of the North of Scotland. The melting point of fluor-apatite is 1630°.

Sulphides. Iron pyrites, FeS_2, and pyrrhotite (magnetic pyrites) Fe_3S_4 are common. Other sulphides, such as copper pyrites, $CuFeS_2$, bornite, Cu_3FeS_3, pentlandite $(Fe,Ni)S$, and mispickel, FeAsS, are only occasionally present in significant quantities. The sulphides are slightly more fusible than the silicates. Pyrrhotite melts at 1183° (E. T. Allen and others), and copper pyrites probably below 1100°. J. H. L. Vogt gives the following melting points:—Cu_2S, 1130°; FeS, 1170°.

Fluorides and Fluosilicates. Among these are:—

Fluorspar, CaF_2

Topaz, $Al(AlF_2)SiO_4$

Cryolite, Na_3AlF_6

Topaz and fluorspar are often found in the marginal facies of granite masses, and fluorspar also appears in syenites and nepheline rocks. Cryolite is only known in some granite-peg-

matites. Fluorspar and cryolite, melting at 902° and 977° respectively, are among the most fusible of all rock-forming minerals. The melting point of topaz is about 1800°.

The Relative Abundance of the Various Minerals and Elements.

F. W. Clarke has made an approximate estimate of the proportions in which the commoner minerals occur in eruptive rocks, with the following result :—

Felspars make up 59 per cent. of all rocks examined.
Metasilicates make up 17 per cent. of all rocks examined.
Quartz makes up 12 per cent. of all rocks examined.
Micas make up 4 per cent. of all rocks examined.
All other minerals together make up 8 per cent. of all rocks examined.

If we compare intrusive with extrusive rocks, in respect of mineralogical composition, it will be found that such differences as appear relate only to the less common minerals. Thus tridymite and cristobalite are restricted to lavas, and leucite and melilite are nearly so restricted; while muscovite, tourmaline, and cancrinite are very seldom seen in lavas, whatever their composition. All other minerals occur indifferently in major intrusions, minor intrusions, and surface flows.

We owe to F. W. Clarke and H. S. Washington the latest and most precise computation of the average chemical composition of eruptive rocks. The first table gives the proportions of the commoner oxides; the second table that of the individual elements. In the case of those elements that amount to less than .001 per cent., the approximate proportion is indicated by a cross in the appropriate position after the decimal point.

TABLE I.

Average Composition in Terms of Oxides.

(Clarke and Washington.)

SiO_2	59.12	CO_2	0.101	Cr_2O_3	0.055
Al_2O_3	15.34	TiO_2	1.050	V_2O_5	0.026
F_2O_3	3.08	ZrO_2	0.039	MnO	0.124
FeO	3.80	P_2O_5	0.299	NiO	0.025
MgO	3.49	Cl	0.048	BaO	0.055
CaO	5.08	F	0.030	SrO	0.022
Na_2O	3.84	S	0.052	Li_2O	0.008
K_2O	3.13	$(Ce,Y)_2O_3$	0.020		
H_2O	1.15				99.984

TABLE II.

Average Composition in Terms of Elements.

(Clarke and Washington.)

1.	Oxygen	46.41	Rubidium	.000,X
2.	Silicon	27.58	Arsenic	,,
3.	Aluminium	8.08	Molybdenum	,,
4.	Iron	5.08	Tin	,,
5.	Calcium	3.61	Bromine	,,
6.	Sodium	2.83	Caesium	.000,0X
7.	Potassium	2.58	Scandium	,,
8.	Magnesium	2.09	Antimony	,,
9.	Titanium	0.720	Cadmium	,,
10.	Phosphorus	0.157	Mercury	,,
11.	Hydrogen	0 129	Iodine	,,
12.	Manganese	0.124	Bismuth	.000,00X
13.	Chlorine	0.096	Tungsten	,,
14.	Barium	0.081	Thorium	,,
15.	Sulphur	0.080	Columbium	,,
16.	Chromium	0.068	Tantalum	
17.	Zirconium	0.052	Uranium	,,
18.	Carbon	0.051	Silver	,,
19.	Vanadium	0.041	Selenium	,,
20.	Strontium	0.034	Platinum	.000,000,X
21.	Nickel	0.031	Tellurium	,,
22.	Fluorine	0.030	Gold	,,
23.	Cerium, yttrium	0.020	Thallium	.000,000,0X
24.	Copper	0.010	Indium	.000,000,00X
25.	Lithium	0.005	Gallium	,,
26.	Zinc	0.004	Germanium	.000,000,000,X
27.	Cobalt	0.003	Radium	.000,000,000,00X
28.	Lead	0.002		
29.	Boron	0.001		
30.	Beryllium	0.001		

REFERENCES.

Allen, E. T.; Wright, F. E.; Clement, J. K.—Amer. Jour. Sci., 1906, *385*.
Allen, E. T.; Crenshaw, J. L.; Johnston, J.—Amer. Jour. Sci., 1912, *169*.
Alling, H. L.—Jour. Geol., 1921, *292*.
Bowen, N. L.—Amer. Jour. Sci., 1913, *577*.
do. —Amer. Jour. Sci., 1914, *207*.
do. —Amer. Jour. Sci., 1912, *551*.
do. and Andersen, O.—Amer. Jour. Sci., 1914, *487*.
do. and Greig, J. W.—Amer. Jour. Sci., 1925, *204*.
Brun, A.—Recherches sur l'exhalaison volcanique; Paris, 1911.
Buddington, A. F.—Amer. Jour. Sci., 1922, *35*.
Chirwinsky, P.—In Doelter's Handbuch Min., vol. 2, pt. 2, 1917, *213*.
Chrustchoff, K. von—Comptes Rendus, 1890, *677*.
Clarke, F. W.—U.S. Geol. Survey, Bull. 588.
do. do. Bull. 770.
do. and Washington, H. S.—U.S. Geol. Survey, Prof. P. 127, 1924.
Day, A. L. and Allen, E. T.—Carnegie Inst. Washington, Publ. 31, 1905.
De Schulten, A.—Bull. soc. min. France, 1880, *150*.
Dittler, E. and Köhler, A.—Tschermak's Min. Pet. Mitth., 1925, *229*.
Doelter, C.—Handbuch der Mineralchemie, 1912.
Fenner, C. L.—Amer. Jour. Sci., 1913, *331*.
Ferguson, J. B. and Merwin, H. E.—Amer. Jour. Sci., 1918, *424*.
Friedel, C. and G.—Bull. soc. min. France, 1890, *129*.
Gorgeu, A.—Comptes Rendus, 1883, *1303*.
Harrington, B. J.—Amer. Jour. Sci., 1894, *17*.
Lemberg, J.—Zeitschr. deutsch. geol. Gesell., 1887, *559*.
Morey, G. W.—Jour. Amer. Chem. Soc., 1914, *217*.
do. and Bowen, N. L.—Amer. Jour. Sci., 1922, *1*.
do. do. —Jour. Phys. Chem., 1924, *1167*.
Mackie, W.—Trans. Edinburgh Geol. Soc., 1925, vol. 12.
Schaller, W. T.—U.S. Geol. Survey, Bull. 610, *106*.
Vernadsky, W.—Bull. soc. min. France, 1890, *256*.
Vogt, J. H. L.—Videnskaps-Selskabets Skrifter, 1903, no. 8.
do. —Norsk Geol. Tidsskrift, 1918, *177*.

CHAPTER III.

THE FUGITIVE CONSTITUENTS OF THE MAGMA.

By fugitive constituents we mean bodies which were present in the magma before freezing set in, but were for the greater part lost during the process of crystallisation, so that they do not commonly appear as rock constituents. These bodies may be gases and vapours which escape from the magma when the external pressure is reduced, or soluble salts which are carried away in solution by magmatic or even meteoric water. There is no part of our subject which remains in greater obscurity than that relating to the fugitive constituents of the magma, their nature, their source, their proportions, and the part they play in the chemistry of the magma and in volcanic eruption. Of recent years controversy has raged especially round the question of the source of the water that is emitted by active volcanoes, a matter of importance in itself, yet one which is not really separable from the bigger question of the fugitive constituents in general and their reactions within the magma.

The evidence relating to the fugitive constituents of the magma is drawn from four sources: first, from observation of active volcanoes and fumaroles in the field; second, from the chemical and microscopical study of the liquids and gases enclosed or occluded within eruptive rocks and rock minerals; third, from the study of contact metamorphism; fourth, from experiments upon the conditions of formation of crystalline silicates.

It has long been realised that the "smoke" of volcanoes consists partly of gases and vapours and partly of so-called volcanic ash, or finely divided lava fragments. As regards the gaseous portion, it has been assumed, perhaps too readily, that it consists chiefly of steam; but the presence of sulphur dioxide and other strong-smelling gases has also been recognised since the earliest times. Now and then, however, the belief that water is a true volcanic product has been challenged. Thus W. Lowthian Green contended that the steam that he observed accompanying the eruptions of Kilauea was merely rain or ground-water,

evaporated by the heat of the lava. We owe to him the following attractive simile :—

"All this steam seems to have no further connection with the forces concerned in the action of the lavas in Kilauea, than the vapours which arise from the body of a hard-worked horse, when a shower of rain has fallen on him, have with the force he exerts in drawing his load."

The extreme view which Green so aptly expresses, has since received the support of A. Brun, whose observations, published in book form in 1911, made no little stir in the geological world. We shall return to this question at a later stage; in the meantime we proceed to record such quantitative data as we possess concerning the composition of the gaseous mixtures actually emitted from volcanic vents.

It should be noted at once that, although many analyses of fumarole and solfatara gases have been made within the last half-century, very few of these refer to material collected just as it issued from the lava. In many instances fumaroles are found outside the crater and round the flanks of a volcano, or even at considerable distances away from it; and gases collected in such situations are not necessarily identical with those originally emitted by the lava. Extensive dilution with air may have taken place while the gases were rising from their distant source, besides reactions of oxidation and double decomposition among the gases themselves. It is not even certain that the gases of such distant fumaroles were derived from lava at all, for even sedimentary rocks give off appreciable volumes of gas when heated. R. T. Chamberlin has analysed the gases given off by sedimentary rocks when heated in vacuo, and it will be interesting to look first at some of his results. The figures refer to volumes of gas per volume of rock.

	Sulphur gases	CO_2	CO	CH_4	H_2	N_2	Total
Non-bituminous shales...	0.00	3.72	0.45	0.11	0.97	0.18	5.43
Sandstones, quartzites ...	0.02	0.29	0.11	0.02	0.17	0.08	0.69

These results illustrate the necessity for collecting directly from the molten lava in order to obtain data which shall really indicate the nature of the gases given off by the magma. Due precautions must also be taken to prevent admixture of the gases with air, since several of the volcanic gases are easily oxidised. It is doubtful whether any single one of the older analyses of volcanic gases by Bunsen, Deville, Fouqué and others refers to material collected under ideal conditions. A few of these

analyses, the material for which seems to have been collected under comparatively favourable conditions, are quoted below.

A. Gases from the lava-flow of 1845, Mt. Hekla, Iceland (Bunsen).

B. Gases from a fumarole in the crater of Vulcano (Deville).

C. Gases from a fumarole in the crater of Vulcano (Fouqué).

D. Gases from lava-stream flowing under the sea, Santorin (Fouqué).

	A.	B.	C.	D.
N_2	78.90	50.77	2.28	21.90
O_2	20.09	10.10	0.52	21.11
H_2	—	—	—	56.70
CO_2	1.01	—	23.40	0.22
H_2S	—	—	—	—
SO_2	—	39.13	trace	—
HCl	trace	—	73.80	—
CH_4	—	—	—	0.07

Undoubtedly the most satisfactory investigations of volcanic gases that have ever been made are those of A. L. Day, E. S. Shepherd and T. A. Jaggar at Kilauea. The gases were collected by thrusting iron pipes, or vacuum tubes with soft glass plugs, into cracks in the crust of the lava lake. All possible care was taken to prevent contamination of the gases by air, but the difficulty of collecting flaming gas is so great that some degree of contamination seems to be unavoidable. In the first collections by Day and Shepherd, water was not estimated, owing to the observers being unprepared for its appearance; nevertheless a large proportion of water condensed in the collecting tubes. In later collections by Shepherd and Jaggar, arrangements were made for determining water. A few representative analyses from the 1917 and 1919 collections are quoted below. The figures refer to volumes per cent. at 1200° C.

CO_2	CO	H_2	N_2	A	SO_2	SO_3	S	Cl_2	H_2O
47.68	1.46	0.48	2.41	0.14	11.15	0.42	0.04	0.04	36.18
11.12	3.92	1.42	—	0.51	—	—	8.61	0.02	77.50
2.65	1.04	4.22	23.22	n.d.	0.16	—	0.70	n.d.	67.99
17.95	0.36	1.35	37.84	n.d.	3.51	—	0.49	n.d.	38.48
33.48	1.42	1.56	12.88	0.45	29.83	—	1.79	0.17	17.97
6.63	0.22	0.15	2.37	0.56	3.23	5.51	—	1.11	80.31
5.79	—	—	7.92	n.d.	4.76	2.41	—	4.08	75.09
1.42	0.05	0.08	0.68	0.05	0.51	—	0.07	0.03	97.09

In summarising the results obtained between 1912 and 1919, Shepherd points out that the principal emanation from Kilauea is water, which averages about 70 per cent. of the total gas evolved. Next in abundance is carbon dioxide, with sulphur dioxide in the third place. Chlorine is relatively scarce, and hydrocarbons are absent or inappreciable. The ratio of argon to nitrogen is about three times as great in the volcanic gases as it is in air.

All the work that has been done on the subject goes to show that the composition of the emanation varies greatly from place to place and from time to time. This is plainly shown even by the small number of analyses quoted above. That this must be the case is evident when one considers that such gases as hydrogen and carbon-dioxide, hydrogen and sulphur-dioxide, react with one another at high temperatures; and further, that some of these gases are capable of reacting even with the silicates and oxides of lava; that, in fact, "whatever may have been the previous opportunities for chemical readjustment among the gases as they rose in solution with the magma and were gradually set free with diminishing pressure, they are still in process of active reaction when discharged into the air." (Day and Shepherd.)

The question must then arise, whether the water which is the chief and in many respects the most interesting component of the emanation was present as such in the lava, or was formed by oxidation of hydrogen at the surface of the lava lake. T. A. Jaggar has shown that air may be carried down into the lava by the foundering of blocks of the frozen crust, which carry air in their pores; thus oxidation may begin even before the gases reach the surface of the lake. But only a small proportion of the water in the emanation could have been formed by atmospheric oxidation, for if much water were formed in this way then the ratio of nitrogen to oxygen in the escaping gases would be much greater than it actually is.

Water may also be formed by reaction between hydrogen and carbon dioxide, with production of carbon monoxide. But the latter gas is quite a minor constituent of the emanation, generally forming less than one per cent. of the whole, so little water can have been produced in this way. In short, we seem to be compelled to believe, with E. S. Shepherd, that "at Kilauea the major constituent is water, and the question as to its meteoric or plutonic origin has been fairly well established in favour of the plutonic."

This conclusion receives strong support from the presence of

firmly held water (as distinct from moisture given off at 100°) in all fresh eruptive rocks. From data collected by H. S. Washington, it appears that the average proportion of combined water in deep-seated rocks is about 0.8 per cent. of the weight of the rock, and in lavas 1.6 per cent., while in certain glassy rocks (pitchstones) there may be as much as ten per cent. of water by weight. E. T. Allen calculates that if the water in average granite were entirely expelled at 100°, under atmospheric pressure, it would occupy a volume thirty times that of the rock, and the water in average basalt under the same conditions would amount to eighty-seven times the volume of the rock from which it was expelled.

Besides the gases that we have discussed, various solid substances condense and form incrustations about volcanic vents and fumaroles. These may be direct sublimates from the magma, or they may result from the decomposition of gases or vapours, or even from reaction between the volcanic gases and the country rocks. Several analyses of such deposits are given by A. Brun.

Vesuvius, eruption of 1906		*Chinyero, eruption of 1909*		*Vesuvius, from cinders of cone*	
Al_2Cl_6 (with Fe,Mn)	9.80	NH_4Cl	79.35	$FeCl_2$ (with Mn)	1.99
NH_4F	6.12	$FeCl_2$	1.86	$MgCl_2$	4.25
NH_4Cl	85.02	NH_4F	9.46	$MgSO_4$	21.96
HCl	0.09	CaF_2	1.21	NaCl	31.50
SO_3	0.15	SiF_4	3.67	KCl	37.39
$CaCl_2$	trace	HCl	3.72	NH_4Cl	1.50
SiF_4	trace	Al_2O_3	trace	H_2O and free acid	1.41
	101.18		99.27		100.00

The incrustations formed about the fumaroles in the Valley of Ten Thousand Smokes, in Alaska, since the eruption of June, 1912, have been studied by J. W. Shipley and E. G. Zies. The gases that issue from these fumaroles, at temperatures up to 645° C., are often strongly acid; sulphur trioxide, hydrochloric acid and hydrofluoric acid have all been detected in them. The most characteristic deposit of the fumaroles, according to Shipley, is amorphous silica, which reacts for fluorine and is believed to have been formed by decomposition of silicon tetrafluoride. Another common type of incrustation is a mixture of gypsum or anhydrite with salt and alum. Ammonium chloride is abundant, and constituted 98 per cent. of the incrustation in one case. Potash alum is also common. Magnetite and red ochre (hematite) are found at almost every vent. Some crystals of magnetite were

examined spectroscopically and chemically by E. G. Zies, and were found to contain the following metals in addition to iron :—

Lead	.005%	Zinc	.47%
Copper	.23	Nickel	.01
Molybdenum ...	.04	Cobalt	.02
Tin	.004	Manganese	.1

Zies states that lead, copper, tin, and zinc are common constituents of the incrustations obtained from many of the fumaroles in the Valley.

The emanation of some East African volcanoes seems to be largely sodium carbonate. C. W. Hobley reports that after the eruption of Donyo L'Engai in 1917, "the country for miles around was covered with a pall of grey volcanic ash and soda," extending as far as twenty-five or thirty miles from the mountain.

We have already mentioned the occurrence of cavities, holding various liquids and gases, within crystals of quartz and other rock-forming minerals. It has been shown by Humphry Davy, Brewster, and many later workers, that the contents of these cavities are usually some of the following substances :—

Carbon dioxide, either liquid or gaseous;
Other gases, such as nitrogen, ammonia, hydrogen;
Water, holding salts and acids in solution;
Chlorides and fluorides of sodium, potassium, calcium;
Sulphates of sodium, potassium, calcium;
Carbonates of sodium, potassium;
Hydrochloric and sulphuric acids;
An iron compound which deposits crystals of göthite, FeO(OH).

The total amount of enclosed fluids and salts present in any particular instance is very small; thus A. W. Wright found in crystals of quartz from Branchville, Conn, only 0.062 per cent. by weight of water, and in addition 1.32 volumes of gas, mainly CO_2; and Day, Sosman and Hostetter have determined the total loss from quartz crystals from Minas Geraes, Brazil, to be 0.025 per cent. up to the temperature of 1100° Cg. An estimation by A. A. Julien of the proportion of water in some Cornish granites was quoted in Chapter I. Small though these quantities are, yet in the gaseous state they may amount to several times the volume of the crystals containing them. Hence if all the gases and liquids confined in the crystals of an eruptive rock represented the total amount originally present in the magma—a most unlikely

supposition—the quantity so found, slight as it is, may yet be sufficient to have impregnated the entire magma and affected its behaviour throughout. It is much more likely that the proportion of fugitive constituents, such as water and carbon dioxide, that is retained in a rock is only an insignificant residue of that originally present in the magma.

In the contact zones surrounding great bosses of eruptive rock, strong evidence is often found of the escape of fugitive constituents from the magma. Studies of contact metamorphism often demonstrate a wholesale transference of silica, alkalies and iron, as well as chlorine, fluorine and sulphur, from the magma to the country rock. Limestone contacts are more instructive than those which involve siliceous or aluminous sediments, because chemical reactions take place between the escaping substances and the limestone, by which the former are retained in the zone of contact alteration. In the metamorphic limestone blocks of Monte Somma, Italy, the following minerals containing chlorine, fluorine, sulphur or phosphorus are found :—

Anhydrite (S)	Galena (S)	Pyrrhotite (S)
Apatite (P,F,Cl)	Haüyne (S)	Scapolite (Cl)
Chondrodite (F)	Humite (F)	Sodalite (Cl)
Clinohumite (F)	Lazurite (S)	Vesuvianite (F)
Cuspidine (F)	Microsommite (Cl,S)	Zinc Blende (S)
Fluorspar (F)	Molybdenite (S)	

Other well-known minerals produced in contact metamorphism, which contain elements foreign to ordinary sedimentary rocks, are :—

Tourmaline (*boron, fluorine*)	Koppite (*fluorine*)
Axinite (*boron*)	Scheelite (*tungsten*)
Sphene (*titanium*)	Datolite (*boron*)
Perovskite (*titanium*)	Topaz (*fluorine*)

It may seem that undue stress is laid upon minerals that are, after all, of comparatively rare occurrence even in contact zones. But the significance of these minerals does not depend on their abundance, but on the unusual elements which they contain and which can only be traced to emanations from eruptive magma. As regards actual abundance, other minerals, such as garnets and pyroxenes, usually predominate greatly, in contact zones, over any of the minerals named above; but then the proof that they owe any of their components to emanations from eruptive magma is not so obvious as it is in the above cases. Neverthe-

less, the transference of silica, iron and alkalies from magma to its country rock can often be demonstrated on an enormous scale, and to a considerable distance. A noteworthy case was studied by W. Lindgren at Clifton, Arizona, where a very pure limestone has been altered into a garnet-pyroxene rock through a contact zone two thousand feet wide. The transformation involves large additions of silica and iron to the limestone. It is interesting to note that the quartz crystals, in the granite which was the cause of the metamorphism, are full of microscopic enclosures of a strong solution of common salt containing an iron compound. Another eruptive rock in the same neighbourhood, which has no such enclosures, has effected very little metamorphism of the limestone. One is forced to believe that the cause of the metamorphism was the escape from the magma of aqueous solutions containing silica and iron.

In a similar case at Bingham, Utah, Lindgren has shown that the limestone has gained silica, sulphur, iron, magnesium, aluminium, and sodium, the additions amounting locally to twenty-nine per cent. of the volume of the limestone.

Striking evidence of the same kind is brought by J. F. Kemp from Tamaulipas, Mexico. In this mining district, highly acid quartz porphyries with a low content of iron cut very pure limestone. In the neighbourhood of the intrusions the limestone develops large quantities of aluminium-iron garnet. Kemp is driven to the conclusion that

" from the intrusive rock has come either highly heated water-gas, or highly heated water itself in the closing stages, and that one or both of these have brought to the limestone the silica, iron oxide, and alumina for production of the silicates. After the production of the garnet and its associates was well under way, they brought in also the copper and iron sulphides which are the commonest ores."

In the Haliburton-Bancroft area of Canada, the contact alteration of limestone by granite is seen on an enormous scale. Great intrusions of gneissose granite invade the Grenville limestone series, and are surrounded by contact zones from a quarter to half a mile wide, in which the limestone has largely been altered into amphibolite (hornblende-rock). In an area of some 3,400 square miles, about one-fourth is underlaid by limestone and amphibolite, and the remainder by gneiss and amphibolite, the amphibolite making up about twenty per cent. of the whole. The changes that have taken place in the contact zone are thus described by F. D. Adams and A. E. Barlow :—

" When the granite-gneiss invades bodies of the limestone, the

changes produced and the phenomena resulting from the intrusion are varied. The products of alteration may be divided into two classes :— (1) Alteration of the limestone into masses of granular pyroxene rock, usually containing scapolite, or into bodies of a fine-grained aggregate of scales of a dark-brown mica. (2) The intense alteration of the limestone along the immediate contact into a pyroxene gneiss, or an amphibolite. The alterations of the first class may be considered as due to the heated waters or vapours given off by the cooling magma, that is, to be of pneumatolytic origin; while the alteration products of the second class probably result from the more immediate action of the molten magma itself."

"A comparison of the analyses shows that the granite at first transfuses into the limestone silica, alumina, oxides of iron, and magnesia, with some alkalies and a small amount of titanic acid. As the alteration progresses, all these constituents continue to increase in amount. But in these later stages of the alteration the alumina, oxides of iron, and alkalies are added in relatively greater proportion than the other constituents, while no further addition of magnesia or lime takes place, the proportions of these constituents remaining essentially the same, the carbonic acid escaping and carrying the rest of the lime with it. This means, speaking generally, that pyroxene and some scapolite were first developed in the limestone, and that later, felspathic constituents increased in amount, the calcite present being removed in solution."

W. G. Foye, studying the same area, showed by analysis of the amphibolite and the unaltered limestone that the material gained by the limestone from the granitic magma had the following composition :—

SiO_2	60.4%
Al_2O_3	22.8
Fe_2O_3,FeO	8.8
MgO	1.7
Na_2O	5.0
K_2O	1.3
	100.0

In all instances, such as these, where there has been a demonstrable addition of material to the contact rock, the question arises whether that material has been

(a) leached out of the sedimentary rock by ground water,
(b) leached out of the eruptive rock by ground water, or
(c) conveyed outward from the deeper parts of the magma by escaping gases and solutions of magmatic origin.

A. C. Lawson, among others, has protested very strongly against a too-ready assumption that the active solutions, in cases such as we have described, are of magmatic origin. He urges that the ground water circulation must be profoundly disturbed

by the injection of heated magma into sedimentary formations, and that an upward circulation of ground water would be established about the periphery of an intrusion, in consequence of which there would be a transference of material leached from the sedimentary rocks *towards* the contact, and of material leached from the hot eruptive rock *away from* the contact; in this way he thinks that all the phenomena which are generally ascribed to the action of magmatic fluids (" mineralizers ") might be accounted for. Lawson rightly holds that until this possibility has been ruled out by the evidence, it is unscientific to claim magmatic fluids as the agents in contact metamorphism.

Unfortunately, it is a most difficult matter to decide, in the field, between the work of heated ground water and that of

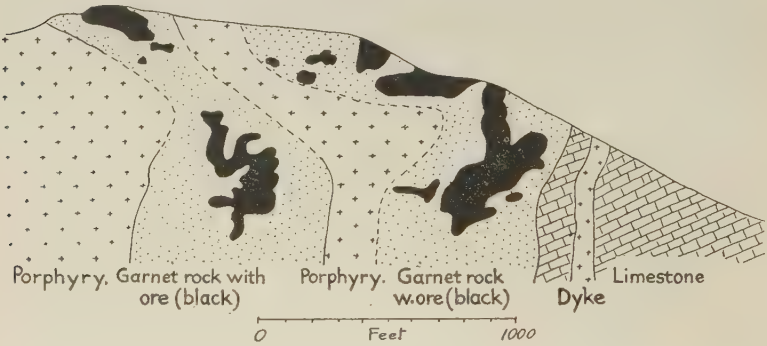

FIG. 3. Section across the contact between porphyry and limestone at White Knob, Mackay region, Idaho. (After J. B. Umpleby.)

magmatic fluids. The problem has been studied very carefully by J. B. Umpleby at White Knob, Idaho, where a batholith of granite (granite-porphyry externally) rises with nearly vertical walls through a thick limestone formation. On the east side of the batholith, the bedding planes of the well-jointed limestone dip towards the granite, thus providing ideal conditions, one might think, for the type of circulation Lawson has pictured; yet there is an almost complete absence of contact minerals and ores about the walls of the batholith. On the other hand, large blocks of limestone which have become embedded in the granite, about the roof of the batholith, have been converted — along with the adjacent granite—into garnet-pyroxene rocks. Umpleby shows that the only change which took place in the limestone during the period of intrusion was recrystallisation, with formation of coarse

grained marble. After the outer few hundred feet of the intrusive mass had solidified, solutions rose *through fissures* in the solid granite-porphyry, which conveyed iron, alumina, silica, and various sulphides from the eruptive into the limestone. This action was accompanied by a reciprocal diffusion of lime into the granite, so that in the end *both* rocks were locally garnetised and charged with ore. (*Figs.* 3, 4.)

Other examples of contact metamorphism, that clearly point to the magmatic rather than the meteoric origin of the mineralising solutions, are described in the chapter on eruptive ore-deposits. Perhaps the most convincing evidence is furnished by the deposits of tinstone and kaolin in granite. The richest deposits of kaolin occupy irregular, pipe-like bodies within comparatively

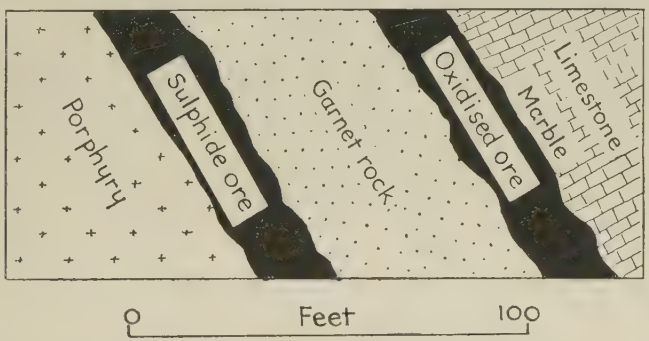

FIG. 4. Vertical section of an ore-body at the junction of porphyry and limestone; White Knob, Idaho. (After J. B. Umpleby.)

fresh granite, which seem to be nothing else than channels through which magmatic solutions made their escape; at least, it is most difficult to account for the curiously localised character of the deposits if they were formed by ground water. Tin ore is also found, in several parts of the world, in pipes of circular or elliptical cross-section, which gradually pinch out and become unpayable when they are followed one or two hundred feet down into the granite. These pipes often carry molybdenite, bismuthine and arsenical pyrites as well as tinstone, and the usual gangue minerals are waxy mica, quartz, tourmaline and fluorspar. The typical tin-bearing lodes of Cornwall and Saxony occupy fissures in granite, within which cassiterite is associated with tourmaline, topaz, lithia-mica, fluorspar, apatite, and sometimes wolfram, or molybdenite and other sulphides. This assemblage of minerals,

containing fluorine, boric acid, lithia, tin, iron, and sometimes tungsten, molybdenum, and arsenic or phosphoric acid, is too peculiar to be due to leaching by ground water. Even the characteristic manner of occurrence, in radially directed pipes and fissures, points to a source within the body of the eruptive rock itself. A. Daubrée showed experimentally that the fluorides of tin, tungsten, boron and silicon are volatile at moderate temperatures, and that they will react with steam at a low red heat, giving oxides and free hydrofluoric acid, as follows :—

$$SnF_4 + 2H_2O = SnO_2 + 4HF$$
$$WF_6 + 3H_2O = WO_3 + 6HF$$
$$2BF_3 + 3H_2O = B_2O_3 + 6HF$$
$$SiF_4 + 2H_2O = SiO_2 + 4HF$$

Daubrée and his followers supposed that tin was emitted from the magma in the form of its fluoride (or chloride), accompanied by fluorides (or chlorides) of tungsten, boron and silicon, and that on reaching cooler zones near the walls of the intrusion, the vapours reacted with steam, depositing cassiterite and quartz directly, while boric acid passed into tourmaline, tungstic acid into wolfram or scheelite, and hydrofluoric acid into topaz, fluorspar, fluor-apatite, and the fluorine-bearing micas.

From this extreme position there has since been a tendency to withdraw. Cassiterite is now known to have been formed in simple quartz veins and felspathic pegmatites, in the absence of minerals containing chlorine or fluorine, and it is therefore certain that some deposits of tinstone and wolfram have been formed in the same way as other common mineral- and ore-deposits, namely, by the agency of hot aqueous solutions. Whether the tin-bearing emanations are ever so hot as to be entirely gaseous is uncertain. J. M. Campbell points out that the boiling-points of tin fluoride (705°) and tungsten fluoride (19°) are so far apart as to make it inconceivable that the two oxides could have been deposited side by side, as they so often are, if they had been given off as gaseous fluorides. But in spite of this modification of the general theory of " pneumatolysis," or deposition of ore by hot gases, we seem to be compelled, by the peculiar composition and distribution of tin lodes and kaolin deposits, to accept the theory which ascribes them to the action of magmatic fluids.

It is remarkable that the nature of the ore-deposits and contact minerals formed about an eruptive contact is largely independent of the chemical composition of the eruptive rock. A.

Lacroix showed that the minerals developed in the contact zone around a lherzolite (olivine-pyroxene rock) in the Pyrenees are the same as those found at granite contacts; namely, scapolite, orthoclase, microcline, plagioclase, mica and tourmaline; although alkalies and boric acids are entirely absent from the lherzolite. V. M. Goldschmidt states that in the Christiania district of Norway the phenomena of contact metamorphism, pneumatolytic alteration and ore-deposition are the same around the basic essexites as around the acid granites and syenites. This evidence seems finally to dispose of the theory that ascribes such contact phenomena to leaching of the eruptive rock by ground water.

It is fair to conclude that there is much in the study of contact metamorphism and contact ore-deposits which lends support to the theory of magmatic emanations. If we had no other evidence bearing on the matter, we should perhaps hesitate to accept this theory, and try instead to explain the extraordinary features of contact metamorphism and ore-deposition in terms of the vagaries of heated ground water; but when we possess evidence of the most direct kind, that eruptive magma can and does hold water and various gases in solution, which it gives off in cooling, then we need not hesitate to refer to this cause all those features of contact metamorphism for which there is no more obvious explanation. But this discussion of the matter shows how necessary it is for the petrologist and the miner to collaborate in studying eruptive contact phenomena, for a fuller knowledge of the fugitive constituents of the magma is of the utmost importance to both.

In many cases of contact metamorphism, there seems to be a transference of alkalies from the magma to the country rock. This is especially indicated by the conversion of shales and slates into felspar-mica rocks, adinoles and glaucophane schists. An instance has been described by V. M. Goldschmidt at Aarvoldaas, Norway, where a hornfels has been enriched with soda to the extent of five and a half per cent. Now all the soda and potash in an eruptive rock like granite are already combined with alumina and silica in the form of felspars, micas, etc.; so to account for the conversion of alumina and aluminium silicates, in the contact zone, into felspar and mica, we must suppose that the magma held an excess of alkalies over alumina, that is, that it held simple silicates, carbonates and other soluble salts of soda and potash. We know of cases where alumina exceeds the alkalies in amount, and it would not be hard to find cases illustrating the predominance of any one of the usual bases of eruptive rocks over

any other. Why not, then, an excess of soda and potash over alumina and ferric oxide?

Any excess of lime, magnesia, or ferrous oxide over alumina goes into non-aluminous silicates like diopside, enstatite and olivine, which, being insoluble and non-volatile, remain among the fixed constituents of the rock. But since all the non-aluminous compounds of the alkalies are soluble in water, any excess of soda or potash over alumina must disappear in solution, either in magmatic or in meteoric water, so its existence can rarely be demonstrated directly. We have seen, however, that small quantities of various simple salts of soda and potash are retained in the fluid-filled cavities of certain minerals. A soluble sodium fluoride (the mineral villiaumite) was found by A. Lacroix in the syenites and pegmatites of the Los Islands, W. Africa. Furthermore, a recent and very accurate analysis of an obsidian from Iceland, by J. B. Ferguson, shows 0.23 per cent. of free sodium chloride and 0.14 per cent. of sodium sulphate; had this magma crystallised instead of freezing as a glass, these salts would no doubt have escaped in solution. It may be added that Zünckel and Hempel have shown experimentally that silicate melts can dissolve as much as 0.86 per cent. of sodium chloride.

Many analyses of soda-amphiboles and soda-pyroxenes, and rocks containing them, actually show an excess of soda and potash molecules over those of alumina and other sesquioxides. In the absence of any negative radicle except silica, we must conclude that this excess is actually present in the form of sodium and potassium metasilicates, which are locked up in pyroxene and amphibole solid solutions.

E. B. Bailey and W. G. Grabham have shown that many British dolerites and basalts have undergone a process of albitization, whereby their original lime-felspars have become replaced by albite. The action is shown to have taken place soon after the rocks had solidified. Bailey and Grabham attribute the phenomenon to the action of magmatic solutions rich in some soluble compound of soda (the carbonate is suggested, but other compounds are possible), and they conclude that "the process may be crudely expressed by saying that *the lava . . . was stewing in a concentrated solution of sodium carbonate.*"

The Importance of the Fugitive Constituents.

In reviewing the facts set out in these pages, we realise that the visible constituents of a rock represented only a part—the non-

volatile and insoluble part—of the original complex mixture of substances that constitutes a magma : no doubt the larger part, and possibly even ninety-nine per cent. of the whole, but still only a part. The special importance of the remaining part, consisting of what we have called the fugitive constituents of the magma, lies in the influence that these constituents have upon the behaviour of the magma as a whole. This influence is shown in the following ways.

(1) *In reducing the viscosity of the magma.* An anhydrous silicate melt, especially if it contains felspar, is extremely viscous. The presence of gases or volatile substances in the melt greatly reduces its viscosity. This is an observation that has been made repeatedly, not only in the laboratory, but also in connection with the flowing lavas of active volcanoes. If the lava, after cooling and losing its gases, is reheated to the temperature that prevailed in the crater or lava-sheet, it does not regain its former degree of fluidity. For example, A. L. Day observed that the lava in the crater of Kilauea is still capable of slight movement at temperatures of about 600°. The same lava will not flow, in the laboratory, until it has been heated to about 1300°. The only possible difference in composition relates to the fugitive constituents.

A particularly neat demonstration of this fact has emerged from the studies of R. B. Sosman and H. E. Merwin on the intrusion temperature of the Palisade diabase in New York. This rock has been intruded in the form of a sill through a bed of felspathic sandstone, and it contains numerous enclosures of the sandstone which shown no signs of fusion. Yet experiment shows that the sandstone melts at about 1150°, while the diabase is not readily fluid until the temperature rises above 1200°. Clearly, at the time of intrusion, the diabase must have been perfectly fluid, and yet its temperature was well below 1150°.

R. T. Chamberlin's observation that rocks of low silica content generally yield (in the crucible) a much larger quantity of gas than more siliceous rocks, may be connected with the fact that basic lavas are more fluid than acid ones. There is, in fact, a strong probability that the cessation of movement in a lava is due as much to the loss of gases as to loss of heat. But it is certain that all lavas have lost a great deal of gas before their expulsion from the crater, and if the residue has such a pronounced effect upon their fluidity, a much greater effect is to be expected in a plutonic magma reservoir before the loss of fluxes has begun. The viscosity of fluids increases with pressure, so the viscosity of

deep-seated magmas would be much greater than that of lavas, were it not for the moderating influence of the fugitive constituents. Here, as in most problems concerning the state of underground magma, we are groping in the dark, yet the study of the structures of deep-seated rocks, and of contact phenomena such as the minute injection of sediments with eruptive rock, suggest a very low degree of viscosity in the magma.

(2) *In promoting crystallisation.* Many of the common rock-forming minerals crystallise readily from dry fusion, as recorded in the last chapter; but others, and notably such very abundant minerals as the alkali-felspars, quartz, mica, and hornblende, can not be induced to crystallise (under experimental conditions) except in the presence of water or a flux such as an alkaline chloride, fluoride or tungstate. The effect of these fluxes may be merely to reduce the viscosity of the melt, but there is some resemblance between the action of fluxes and that of catalysts, for a very small quantity of flux may cause a large amount of crystallisation. For example, Hautefeuille showed that amorphous alumina can be made to crystallise by the action of steam and hydrochloric acid at red heat; the acid is not used up, so a small quantity of it is capable of converting an indefinitely large amount of alumina into corundum. Many other examples of the use of fluxes in promoting crystallisation were given in Chapter II. and they need not be repeated here.

Charles Darwin studied the lavas of Ascension Island during the voyage of the " Beagle," and he has recorded that " the extent to which the minerals have crystallised can be distinctly seen to be connected with the greater or less size, and with the number, of the air-cavities or fissures " in the lavas.

J. P. Iddings has shown that in the obsidians of the Yellowstone National Park, the parts which are richest in gas bubbles have a larger proportion of minute crystals than the parts that show less evidence of gas. A precisely similar observation has been made by P. A. Wagner in recording some experiments with fused kimberlite. It is true that in those cases the observation is open to another interpretation, namely, that the crystallisation of the melt has caused the liberation of the dissolved gas; but since the degree of crystallisation was small, it is more likely that the gas caused the crystals than the crystals the gas bubbles. W. H. Emmons and E. S. Larsen, in their description of the rhyolites of the Creede district of Colorado, express the opinion that the degree of crystallisation of these lavas depended more on the rate of loss of gases than on the rate of cooling.

(3) *In lowering the freezing point of the magma.* It is well known that the effect of dissolving a salt in water is to lower the freezing point of the solution, the degree of lowering being proportional to the quantity of salt added. This is sometimes known as Blagden's Law, but it is better stated in the more generalised form given to it by Raoult :—

"Every substance, solid, liquid or gaseous, when dissolved in a definite liquid compound capable of solidifying, lowers its freezing point." (Raoult-Blagden Law.)

To this may be added the further extension known as Raoult's Law :—

"In a constant weight of a given solvent, all the physical molecules, whatever their nature, produce the same lowering of the freezing point."

What is true of other liquids in this respect is true of a silicate magma. The presence in it of the volatile substances which we have described has the effect of depressing the freezing point of the magma below that of a pure silicate melt. The amount of depression depends entirely on the mass of the substances in question : a quantity which, as we have seen, we possess no means of estimating. But since water, hydrochloric and hydrofluoric acids, and other fugitive constituents of the magma are compounds of low molecular weight, and since the effect depends only on the *number* of molecules present, it is clear that the depression of the freezing point may be much larger than the absolute quantity of gases in the magma would lead us to expect.

G. W. Morey has heated silicate glasses along with water in gas-tight bombs, and obtained mobile liquids at temperatures considerably below the melting point of the dry glass. Many other illustrations of this effect will be given in a later chapter.

We have already discussed the fact that, on the whole, deep-seated rocks seem to have completed their crystallisation at lower temperatures than lavas. It is not unreasonable to connect this with the greater concentration of fugitive substances in deep-seated magma.

As the crystallisation of a magma progresses in its underground reservoir, the water and other fugitive constituents should tend to become concentrated in those portions of the magma which longest remain fluid. Now, such late-crystallising residues of the magma are represented by pegmatite and aplite veins and the contents of drusy cavities and gas vesicles. It is in these situations that we find acidic, basic and hydrous silicates most strongly

developed, testifying to the concentration of water; there, too, we find boric acid, otherwise little known as a rock constituent, entering into the composition of tourmaline and datolite; fluorine appearing in topaz, tourmaline, fluorspar, zinnwaldite, cryolite, apophyllite, apatite, and many rarer minerals; chlorine in apatite, scapolite and sodalite; phosphoric acid in apatite, xenotime, monazite, and other rare phosphates. E. S. Bastin has shown that many of these pegmatites completed their crystallisation below 575° C.

(4) *In segregating, transporting, and depositing metallic ores and other useful minerals.* This forms the subject of Chapter XVI.

REFERENCES.

Adams, F. D. and Barlow, A. E.—Canada, Geol. Survey, Mem. 6, 1910.
Allen, E. T.—Jour. Franklin Inst., 1922, *29*.
do. and Zies, E. G.—Nat. Geographic Mag., 1923, *75*.
Bailey, E. B. and Grabham, G. W.—Geol. Mag., 1909, *250*.
Bastin, E. S.—U.S. Geol. Survey, Bull. 445, 1911.
Brewster, D.—Trans. Roy. Soc. Edinburgh, 1826, *1*.
Brun, A.—Recherches sur l'Exhalaison volcanique; Paris, 1911.
Chamberlin, R. T.—Carnegie Inst. of Washington, Publ. 106, 1908.
Darwin, C.—Geological Observations: London, 1891, *78*.
Davy, H.—Phil. Trans. Roy. Soc., 1822, *367*.
Day, A. L. and Shepherd, E. S.—Bull. Geol. Soc. Amer., 1913, *573*.
do. ; Sosman, R. B.; Hostetter, J. C.—Amer. Jour. Sci. 1914, *1*.
Emmons, W. H. and Larsen, E. S.—U.S. Geol. Survey, Bull. 718, 1923.
Ferguson, J. B.—Bull. Geol. Soc. Amer., 1915, *259*.
Foye, W. G.—Amer. Jour. Sci., 1915, *413*.
Green, W. L.—Vestiges of the Molten Globe; Honolulu, 1887.
Hobley, C. W.—Jour. E. Africa and Uganda Nat. Hist. Soc., 1918 *339*.
Iddings, J. P.—U.S. Geol. Survey, 7 Ann. Rep., 1885, *265*.
Jaggar, T. A.—Amer. Jour. Sci., 1917, *161*.
Julien, A. A.—Jour. New York Micro. Soc., 1885, *140*.
Kemp, J. F.—Econ. Geol., 1907.
Lacroix, A.—Nouvelles Archives du Museum, Paris, 1911.
Lawson, A. C.—Univ. California, Bull. Dept. Geol., 1914, *219*.
Lindgren, W.—(Clifton) U.S. Geol. Survey, Prof. Paper 43, 1905.
do. —(Bingham) Bull. Geol. Soc. Amer., 1924, *507*.
Morey, G. W.—Jour. Amer. Chem. Soc., 1914, *215*.
Shepherd, E. S.—Bull. Hawaii Volcano Observ., 1919, 1920, 1921.
Shipley, J. W.—Amer. Jour. Sci., 1920, *141*.
Sosman, R. B. and Merwin, H. E.—Jour. Washington Acad. Sci., 1923, *389*.
Umpleby, J. B.—U.S. Geol. Survey, Prof. Paper 97, 1917.
Wagner, P. A.—The Diamond Fields of Southern Africa, 1914.
Wright, A. W.—Amer. Jour. Sci., 1881, *209*.
Zies, E. G.—Nat. Geographic Mag., 1924, *157*.
Zünckel, R. and Hempel, W.—Zeitschr. Vulkanologie, 1917, *256*.

CHAPTER IV.

THE MAGMA AND ITS WALLS.

We have discussed the composition of eruptive rocks, both qualitatively and quantitatively; we have described the fugitive constituents of the magma, chiefly in a qualitative way; from the data so gathered we must form the best idea we can of the composition of a body of magma before freezing sets in. The magma, at this stage, is a solution of silicates of eight or more common metals, together with smaller quantities of other compounds, such as titanates, phosphates, and sulphides, and with an unknown, though probably small, content of certain volatile and water-soluble compounds, including water itself and either free or combined carbonic acid.

After the composition of the magma, we are concerned to know its temperature, and the pressure under which it is confined within the earth crust.

The pressure that prevails in a magma-reservoir has three distinct components. The chief of these, unless the magma has climbed very nearly to the surface, is the weight of the overlying layer of rock. This may be estimated at about 400 atmospheres per mile below the surface. It is open to question whether any body of rock, now visible at the surface, crystallised at a greater depth than—say—three miles. Clearly, the greater the depth of consolidation, the more erosion must have taken place before the rock was laid bare, consequently the more incomplete the stratigraphical evidence by which the depth of consolidation can be judged. For this reason J. C. Ward was unable to decide between quantities so different as 12,000 feet and 30,000 feet, for the depth of consolidation of the granites of the Lake District of England. The roof of the Finmarken granite laccolite, in Norway, was about 1,600 metres thick, according to W. C. Brögger J. Barrell showed that the Marysville batholith of Montana lay originally within 4,000 feet from the surface; and Leith and Harder give the same figure for the Iron Springs laccolite in Utah. It is likely, therefore, that in the case of all intrusions except perhaps the largest and most ancient batholiths, the pressure due to the weight of the roof did not exceed 1,200 atmospheres at the

time when freezing took place, and that it was generally a good deal less than that.

The second component of the total pressure is the vapour-pressure of the dissolved gases (water vapour, carbon dioxide, etc.). In the almost complete absence of data relating to the concentration of gases in natural magmas, it is impossible to form a measure of this component. If the concentration is low enough, the vapour pressure may be negligible in comparison with the pressure of the overlying rock; but when the magma begins to crystallise, the whole of the gases become concentrated in the diminishing residue of liquid, and the vapour pressure must rise steadily, unless the gas is able to escape by way of openings in the roof and walls of the reservoir.

The third component of the total pressure only comes into operation if the viscosity of the magma is so high as to prevent it from accommodating itself at once, by change of shape, to lateral pressure such as that which accompanies mountain-building movements. Since all available evidence indicates a high degree of fluidity in the magma, this factor will not be effective until the magma has nearly completed its crystallisation.

If the pressure prevailing within a magma reservoir is difficult to estimate, the temperature is still more uncertain. Sorby's method, already referred to, was based on measurement of the contraction undergone by the fluid enclosures in quartz crystals; it yielded values ranging about 300° to 350°. This, as well as Lehmann's estimate of 500°, refers to highly siliceous rocks such as granites and trachytes. The method of F. E. Wright and E. S. Larsen, which depends on the use of quartz as a "geological thermometer," points to the majority of the quartz-bearing rocks having crystallised between 575° and 800°. The principle of the method may be explained briefly.

The mineral which we know as quartz varies slightly in crystalline form according to whether it was formed at a temperature above or below 575°. The kind of quartz formed below 575° is known as α-quartz, and the high temperature variety as β-quartz.

"If at any time in its history a particular piece of quartz has passed the inversion point and been heated above 575°, it bears ever afterwards marks potentially present which on proper treatment can be made to appear, just as an exposed photographic plate can be distinguished at once from an unexposed plate on immersion in a proper developer, although before development both plates may be identical in appearance." (Wright and Larsen.)

The critical points in the discrimination of the α and β forms are as follows :—

For the α form : (1) presence of faces of the trigonal trapezohedron; (2) unequal development of the rhombohedral faces; (3) twinning lines regular and sharply marked; (4) intergrowths of right- and left-handed forms frequent and regular; (5) habit of crystals is prismatic; (6) absence of cracks.

For the β form, or for α crystals which have transformed from the β condition : (1) absence of faces of trigonal trapezohedron; (2) equally developed pyramid faces; (3) twinning lines very irregular; (4) intergrowths of right- and left-handed forms very irregular; (5) habit is pyramidal; (6) crystals are much cracked.

The granites and granite-porphyries which were tested by Wright and Larsen showed as a rule the presence of β-quartz; the only specimens of α-quartz were derived from pegmatite veins.

E. S. Bastin used the method of Wright and Larsen to determine the crystallisation temperatures of the gem-bearing pegmatites of Maine; he reached the following conclusions :—

"... Although many of the finer-grained pegmatite masses and most of the graphic intergrowths of the coarser pegmatites crystallised at temperatures above 575°, the coarser and more siliceous portions—the portions characterised by the cavities, and hence presumably richer in gaseous or fluid constituents—crystallised at temperatures below 575°. The portions characterised by high and low temperature quartz are commonly so intimately associated in the same pegmatite mass that it seems unreasonable to assume great differences in the temperature of crystallisation of different portions. It is probable, therefore, that the whole mass of many of the coarser pegmatites crystallised not far from the inversion point of quartz; that is, not far from 575° C."

E. F. Holden has shown that rose-quartz, a variety which occurs in some pegmatites and which owes its colour to manganese, is decolorised by heating to about 575°, and that quartz formed above that temperature is colourless, even when it holds enough manganese to have given it a rose colour.

The conversion of quartz into tridymite at 870° has already been discussed. Observation shows that while tridymite is a fairly common constituent of acid lavas, it never appears in plutonic rocks. It is found, too, that quartzose rock fragments which have been picked up by flowing lavas often have their quartz changed to tridymite. Similar enclosures are very common in plutonic rocks, but in these the transformation is not

observed. Thus, if we must accept 575° as the lower limit, it seems that we are also confined to 870° as the upper limit of the temperature experienced, during the period of crystallisation, by the more siliceous deep-seated magmas. But since there is a considerable difference in density between quartz and tridymite, the transition point ought to be raised by pressure. C. N. Fenner has discussed this point, but finds it impossible to form any reliable measure of the effect. V. M. Goldschmidt suggests that an increase of pressure by 400 atmospheres may raise the transition point by 100° or more, but Wright and Larsen think it probable that " pressure has but a slight effect in raising or lowering

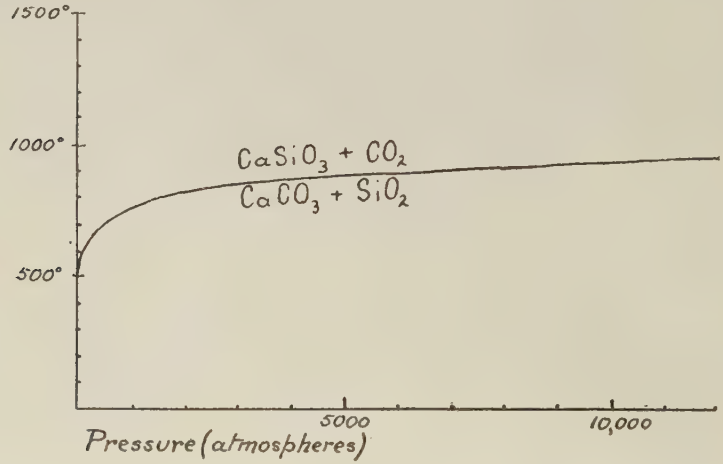

Fig. 5. The stability-curve of calcium carbonate and silica. (V. M. Goldschmidt.)

such an inversion point, and that whenever quartz appears in nature it was formed at a temperature below 870°." (800° in the original paper, but afterwards corrected to 870°.)

A further application of the " geological thermometer " principle is possible when limestone occurs in contact with an eruptive rock or among the fragments enclosed in the latter. At ordinary pressure the reaction

$$CaCO_3 + SiO_2 \Longleftrightarrow CaSiO_3(\text{wollastonite}) + CO_2$$

takes place between 500° and 600° C. The effect of higher pressures upon the temperature of reaction is shown in *Fig.* 5, after V. Goldschmidt. It will be seen that if the pressure under which a given rock crystallised can be estimated from

stratigraphic data, then the presence or absence of wollastonite in the contact zone will enable one to set either a lower or an upper limit to the temperature of the magma at the place of contact. P. Eskola points out that the association of quartz with calcite at such a contact proves conclusively that the transformation temperature was not reached, but the appearance of wollastonite does not prove the contrary, for it may be formed at temperatures below the transformation curve if silica meets lime in other form than the carbonate, and no free carbon dioxide is present. Eskola finds that wollastonite is rare in the contact-altered Archaean limestones of Finland, but quartz is often present. It should be noticed that the temperature indicated in this way is not the freezing temperature of the magma, or that of any of its constituents, but is the maximum temperature which prevailed at any time during which the magma and the limestone were in contact.

C. W. Wright studied the production of garnets in the contact zones between granitic rocks and limestone. These garnets are often birefringent, but this property is found to be destroyed when the garnets are heated for a few hours at 800°. This observation makes it very probable that the intrusion-temperature of the granite was less than 800°.

A further point on the geological thermometer scale is fixed by the irreversible transformation of wollastonite to pseudo-wollastonite, which takes place, according to E. T. Allen and W. P. White, at 1180° and is practically unaffected by pressure. Pseudo-wollastonite is unknown in nature, although it is commonly formed in furnace slags. Only wollastonite is formed by the contact metamorphism of limestones, from which we may conclude with a close approach to certainty, that the various magmas which have effected this kind of metamorphism in limestones were intruded at temperatures lower than 1180°.

A similar conclusion is indicated by the study of the transformation nepheline-carnegieite, which takes place at 1248°. N. L. Bowen writes that "in the event of the discovery of a natural carnegieite, its crystallisation above 1200° could be asserted with but little fear of error." But carnegieite has not been identified in nature, and Bowen concludes that most natural nepheline crystallised as such.

An upper limit to the range of magmatic temperatures is also indicated by the following observations. The dolerite (diabase) sill of the Palisades of the Hudson, New York, is intrusive in a

series of felspathic sandstones and shales and holds many fragments of these. The melting temperature of these rocks has been determined by R. B. Sosman and H. E. Merwin, who found that both the sandstone and the shale were more than half-melted after heating for seventy-five minutes at 1150°. Yet fragments of these rocks which were completely enveloped by the magma retain their original structures and show no sign of having been fused, thus proving that the intrusion temperature of the dolerite magma was below 1150°.

A useful summary of the different methods that have been used to determine geological temperatures is given by J. Königsberger. Very high estimates have sometimes been made of the temperature of flowing lava. J. Friedländer, for example, heated pieces of lava in the laboratory until they showed the same degree of luminosity as the active lava previously observed in the craters of Kilauea and Savaii, and concluded that the temperature of the latter must have been above 1600° C. The method is clearly a very gross one, but besides that, Day and Shepherd showed that combustion of gas is taking place all the time at the surface of the lava lake in Kilauea, so that the surface layer must be expected to show a considerably higher temperature than the lava underneath. T. A. Jaggar has since made actual measurements of the temperature of the lava at Kilauea, both at the surface and beneath it. He found that in lava fountains and domes where active combustion of gas was going on, the temperature rose as high as 1350°; but three feet below the surface of the lava the temperature was only 750° to 850°. Jaggar's procedure was to put Seger cones of known melting point into steel pipes, and thrust these down into the active lava. His measurements, although still rather rough, are far more reliable than any of the earlier estimates.

A. L. Day and E. T. Allen have ascertained that the biotite in the lava of Lassen Peak, California, begins to decompose at 840°, and melts at 1050°, under atmospheric pressure. The crystallisation of the biotite must therefore have taken place at a temperature lower than 840°, unless this transformation point is greatly affected by pressure.

G. W. Tyrrell has tried to estimate the intrusion-temperature of a basalt dyke on the island of Arran, Scotland, by the effect it has had on enclosed fragments of pitchstone. The latter rock contains well-formed crystals of quartz, orthoclase and andesine, in a glassy base. The orthoclase crystals have been partly

melted; the andesines are only slightly affected; the quartz crystals are cracked but not melted. The melting point of pure orthoclase is 1170°, that of andesine (Ab_2An) is 1375°, so Tyrrell concludes that the temperature of the basalt was between these limits. The argument is scarcely conclusive, since the product of melting was not analysed—it might, for example, be a quartz-orthoclase eutectic, with a melting point considerably lower than that of pure orthoclase—so no great value is to be attached to these figures; yet the observations certainly indicate that the temperature of the basalt was higher than that of any known plutonic magma.

H. A. Brouwer has observed the melting of quartzite enclosures in the andesitic lavas of Merapi, Sumatra, and the conversion of quartz into tridymite. The melting point of the quartzite is not known, and it cannot be assumed to be the same as that of pure quartz, so the observations only prove that the temperature of the lava exceeded 870°. A. Sigmund has recorded the melting of quartz grains in a magma-basalt at Furstenfeld, Austria. Each grain is surrounded by a mantle of yellowish glass, but clearly this is explained more readily by solution than by melting of the quartz, and it is not clear that the temperature was above the tridymite transformation-point. On the other hand, H. H. Thomas describes basaltic dykes in Mull, Scotland, which have attacked the quartz grains of invaded sandstones, and have given rise to tridymite fringes round the undissolved portions of the grains. With cooling, the tridymite reverted to quartz, but the shape of the tridymite crystals was retained, proving that the transformation point was passed.

An observation which seems to demonstrate an unusually high temperature in lava has recently been made by A. Amstutz. An olivine-basalt at Dorgali, in Sardinia, encloses fragments of biotite-granite, which have been recrystallised with formation of leucite. If the leucite was formed at the expense of biotite, the temperature need not have been higher than about 1000°; but if it was formed from orthoclase, as is likely, then the temperature must have been in the neighbourhood of 1175°. The only weak point in this demonstration is that one does not know how the orthoclase-leucite inversion point is affected by the presence of other substances.

V. M. Goldschmidt has described enclosures of granite in lavas of Spitzbergen, in which the biotite has been melted, producing a pale brown glass full of needles of ortho-pyroxene.

These lavas were accordingly hotter than the melting point of biotite, but not so hot as the transformation point of orthoclase.

Putting our conclusions together, we may say that *there is an entire lack of evidence that any body of deep magma ever had a temperature higher than* 1170°, *or that it even approached that temperature; in very many cases the temperature does not seem to have exceeded* 870°. In the case of surface magma (lava) the top layer may be heated up, by gas reactions and oxidation, to 1300° or more, but there is no reason to think that the body temperature of lava ever reached such a figure. It may be granted, however, that surface magma, and small bodies of magma in dykes near the surface, may show appreciably higher temperatures than deep magma.

We may now turn to the consideration of a body of deep magma which is exposed to such conditions of temperature and pressure as we have discussed in these pages. It is contained within a chamber whose walls are formed of rocks of familiar character; that is, of eruptive rocks such as granite and dolerite, and of siliceous, aluminous, and calcareous sediments, or the metamorphic equivalents of these. Eruptive rocks play a very large part in the composition of the lithosphere, and this must become steadily greater with increasing depth. F. W. Clarke has estimated that eruptive rocks form ninety-five per cent. of the crust, down to a depth of ten miles. The remaining five per cent. he allots to sedimentary rocks in the following proportions: shale, 4 per cent.; sandstone, 0.75 per cent.; limestone, 0.25 per cent. Towards the surface, of course, the ratio of sedimentary to eruptive matter increases rapidly.

A question of fundamental importance now arises: to what extent is the composition of the magma modified by assimilation of the containing walls?

In view of the general similarity between the molecules of the magma and those that form the minerals of the country rocks, it seems almost inevitable that some solution of the walls should take place; and in certain cases, such as the contact of siliceous magma with limestone, the door would seem to be open for chemical reaction to take place as well. The two possibilities will be considered separately, namely

(a) assimilation of silicates and quartz;
(b) chemical reactions involving silication and desilication.

Assimilation of silicates and quartz. The evidence bearing on the question of assimilation of country rocks by the magma is often of a curiously evasive kind, owing to solution and contact metamorphism going on together. The escape of alkalies and silica from the cooling magma has sometimes produced an intense alteration of aluminous sedimentary rocks in the contact zone. Under the influence of these magmatic emanations, felspar and mica are developed at the expense of the aluminium silicates that constitute clay, shale and slate. In the innermost portion of the contact zone around a granite batholith, this process has often gone so far that the sedimentary rock is wholly converted into a crystalline aggregate of quartz, alkali felspar and mica, which is hardly to be distinguished from the granite itself save by some difference of texture, combined with unusual richness in dark mica or hornblende. Now, by the purely mechanical disintegration of such contact rocks, crystals of quartz, felspar, and mica or hornblende may be incorporated in the eruptive magma without suffering solution, and in the resulting solid rock they may be indistinguishable from true magmatic minerals. Thus the phenomena produced by the solution of country rock may be imitated, and their study complicated, by incorporation of the solid products of metamorphism.

Another difficulty that arises in studying contacts of this kind is that one seldom knows what the composition of the original intrusive was. The rock exposed at the surface, which passes for the unmodified eruptive, is only the top layer of a great reservoir of magma, and it may itself be a composite thing produced by complete assimilation of sedimentary material. C. N. Fenner has described some beautiful cases of admixture of granitic and metamorphic rocks in New Jersey. The purest variety of the granite contains little but microcline, albite and quartz, and the dark coloured metamorphic rocks, which form bands and indefinite streaks within the granite, consist of biotite, hornblende, quartz, microcline and albite. Fenner remarks that "in such occurrences as show bands of basic rock in largest amount, the adjacent granite contains the largest quantity of dark silicates, and where inclusions are rare, the granite is very light coloured and nearly free from ferro-magnesian minerals, and it seems probable that the invading magma was composed essentially of quartz and felspars, and that the dark minerals, even in massive granite, were derived to a large extent from the rocks which were invaded."

W. J. Miller has assumed a very extensive assimilation of country rock (metamorphic rocks of the Grenville Series) in order to explain the phenomena shown by the granite masses of the Adirondack Mountains, New York. The top of Prospect Mountain is formed of fine-grained, gray biotite-granite, which is very homogeneous except for occasional patches and stringers of Grenville gneiss. Passing southward down the mountain side, this rock shows fewer and fewer inclusions, passing into medium-grained biotite granite and eventually into biotite granite porphyry. Passing westward down the mountain side, however, the fine-grained granitic rock becomes coarser and holds more and more numerous and clearly-defined inclusions of Grenville gneiss, and passes eventually into biotite-garnet gneiss and quartzitic gneiss at the base of the mountain. As there is a perfect transition from the gray, granitic rock into the granite porphyry, on the one hand, and into Grenville gneiss on the other, it is held that the gray rock was formed by solution of Grenville material in the granite prophyry magma.

W. H. Collins makes out a strong case for extensive assimilation of sedimentary material by granite in the Onaping area, Canada. Batholiths of biotite-granite have invaded a complex of ancient schists which represent, in a highly metamorphic state, a system of slates, conglomerates, arkoses, tuffs and lava beds. The more usual types are chlorite schists, sericite schists and "iron formation," or banded slates containing much magnetite and hematite. Where the biotite granite makes contact with the schists it is found to be full of blocks of the schist, showing the usual stages of disintegration, the contact itself "resembling in miniature an irregular, deeply embayed coast-line fringed with a myriad of islands and islets." The iron-rich inclusions are surrounded by dark areas of rock so rich in hornblende as to be nearly black, fading away outwards into normal biotite granite; these areas are clearly due to assimilation of fragments of iron-formation, as a result of which the biotite granite has transformed itself locally into hornblende rock. Near Burwash Lake many bodies of iron formation are enclosed in the eruptive, but the schists which normally lie above and below the iron formation have all disappeared except for swarms of partly digested fragments that lie in the granite. It is concluded that over an area of at least 50 square miles a thickness of schists measurable in hundreds, if not thousands, of feet was absorbed by the magma, and that the iron formation survived by virtue of being the most

FIG. 6. Thin sections showing assimilation of ferruginous slate ("iron formation") by granite; Onaping, Canada. (W. H. Collins.) Magnification, 15 diameters. I, normal biotite granite; II, hornblende-plagioclase rock, two inches away from an enclosure of ironstone; III, actinolite-grünerite-epidote rock at the margin of the enclosure. [A = actinolite; B = biotite; E = epidote; G = grünerite; H = hornblende; M = magnetite; Mi = microcline; O = orthoclase; P = plagioclase; Q = quartz; T = titanite (sphene).]

refractory material in the schist complex encountered by the granite. (*Fig.* 6.)

Interesting cases of solution of granite by a later doleritic magma are described by F. P. Mennell in Southern Rhodesia. Dolerite dykes near Bulawayo cut the granite of the Matopo Hills, and incorporate fragments of granite which are sometimes so abundant that the rock resembles a conglomerate more than an eruptive. Under the microscope the quartz grains show corroded outlines; the felspars have a cloudy or mottled appearance internally, but marginally they are fringed with clear, new felspar substance, or they may show fresh micropegmatite occupying cavities formed by corrosion. Where granite enclosures are abundant, the dolerite becomes paler in colour, as if much granite had been completely assimilated. A chemical examination of the pure and the contaminated dolerite is needed to complete the evidence in this case. (*Frontispiece.*)

The converse occurrence, solution of dolerite (diabase) in granite, has been observed by A. G. Högbom at Ragunda, Sweden. The granite sends a network of veins and dykes into the dolerite, giving rise to an " intrusion breccia " which consists of fragments of dolerite cemented and more or less altered by the granite. (*Fig* 7.) Högbom claims that intermediate rocks, characterised by chemical and structural inconstancy, have been produced by the assimilation of dolerite by granite. In a still more remarkable instance in Angermanland, Högbom describes the invasion of a coarse-grained anorthosite (plagioclase-rock) by a granitic magma which has eaten its way in between the felspars of the anorthosite, thus giving rise to a peculiar rock consisting of large anorthite crystals lying in a base of quartz and orthoclase.

An astonishingly complete case of assimilation of included rock fragments is described at Julianehaab, Greenland, by N. V. Ussing. An augite syenite consisting of felspar, augite and olivine holds immense included blocks of sandstone and countless small fragments. One of the great blocks has a volume exceeding 200,000 cubic metres. Round each of these inclusions there is a zone of soda-granite, formed by solution of sandstone in the syenite. The soda-granite has been completely fluid, since it sends small veins into the sandstone and the surrounding augite syenite. Ussing shows by comparing the chemical composition of the rocks that " the quantity of solid material (sandstone) which has been absorbed by the magma is probably not less than half the weight of the absorbing magma."

FIG. 7. Assimilation of dolerite (diabase) fragments by granite at Hammarforsen, Sweden. A. G. Högbom. (Two-sevenths of natural size.)

[*To face page* 60.

A. Harker has described a case of solution of gabbro in granophyre at Carrock Fell, Cumberland. Passing outwards from the heart of the granophyre area, the rock becomes less and less siliceous and develops increasing quantities of augite, apatite and iron ores. The marginal facies of the granophyre, which is in contact with the gabbro, is a compact, dark rock with a specific gravity of 2.925, that of the normal rock being 2.670. The facts lead to the conclusion that portions of the gabbro were assimilated by the granophyre magma. The augite, being the most fusible mineral, seems to have been dissolved completely, since the augite of the granophyre is not identical with that of the gabbro. The felspar seems also to have been dissolved in great part, though it is considered possible that some of the relatively large crystals of plagioclase seen in the modified

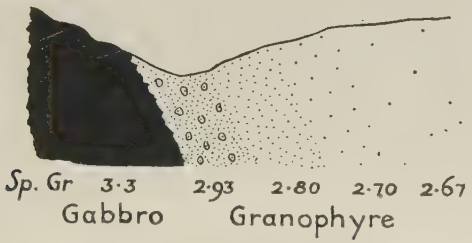

FIG. 8. Section illustrating the modification of the Garrock Fell granophyre by incorporation and assimilation of gabbro. (After A. Harker.)

granophyre have been directly derived from the older rock, for they frequently show a clear border surrounding a turbid interior of rounded shape and corroded appearance. The less fusible iron ore and the apatite of the gabbro have been simply incorporated by the granophyre without undergoing solution. (*Fig.* 8.)

A very similar case has been studied by W. J. Sollas in the district of Carlingford, Ireland. The top of the hill of Barnavave is gabbro, the base is granite and granophyre (granite-porphyry), the junction being well exposed. Dykes of granophyre cut the gabbro, and lumps of gabbro are enclosed in the granite, sometimes forming intrusion breccia. Detached crystals from the gabbro lie in the granophyre, and in the absence of field evidence they would be mistaken for true constituents of the latter. From the large plates of augite (diallage variety) in the gabbro smaller augite grains have been formed, and occasionally some biotite or

green hornblende. The basic plagioclase crystals of the gabbro have developed mantles of orthoclase, and the hybrid rock so produced might be called quartz-biotite diorite (Sollas).

The contamination of gabbro or norite magma by incorporation of sedimentary and metamorphic material has been studied closely by H. H. Read in Aberdeenshire. Magma which normally gives rise to norite (plagioclase-hypersthene rock) has, owing to solution of its country rock, produced rocks which contain cordierite, sillimanite, spinel, garnet, and hornblende, together with orthoclase and quartz. It is shown that in the process of assimilation, there is an interchange of material between the magma and the enclosures, the magma yielding lime, magnesia, and possibly soda to the enclosures and receiving alumina and potash in exchange. Read believes that after this interchange has taken place, the modified enclosures sink, leaving the magma lighter and more acid than before, so the final product of contamination may be a fairly normal-looking granitic or dioritic rock composed of quartz, biotite, hornblende and felspar.

It should be observed that the highly aluminous minerals andalusite, sillimanite and cordierite are never found in eruptive rocks except in circumstances which suggest that there has been assimilation of aluminous sediments. They are not uncommon in the marginal parts of granite masses. Spinel is also found in such circumstances, and even corundum. K. Busz has described a granitic dyke rock near South Brent, Devonshire, which cuts slate and encloses masses of it. Round about these fragments there is an abundance of small crystals of corundum, decreasing in number farther away from the slate. Busz holds that the corundum crystallised out of the magma, which was locally oversaturated with alumina in consequence of having dissolved some of the slate. The same explanation was used by L. V. Pirsson to explain the occurrence of sapphires in a dyke rock at Yogo Gulch, Montana.

Chemical reactions involving silication and desilication. The clearest evidence of solution at eruptive contacts will naturally be found in cases where the country rock differs very widely in composition from the invading magma, for then no amount of contact metamorphism can completely obscure the nature of the country rock, and any appreciable assimilation of it is bound to be evident in the changed composition of the eruptive near the junction. Such a case would be, for example, the contact of a

granitic magma with a limestone. We shall see that such contacts have in point of fact furnished some of the most convincing evidence we possess of magmatic assimilation. As a first illustration we shall consider the classic work of A. Lacroix on the granites of the Pyrenees.

The granite massif of Quérigut is in contact with schists, quartzites and limestones of Palæozoic age, through which it is believed to have risen by dissolving them away, the schists yielding easily to dissolution while the limestones were more resistant. Consequently great masses of more or less altered limestone are completely enclosed in granite, and as a result of partial solution of limestone the granite loses its quartz and is locally converted into hornblende-mica-diorite, or where solution has been still more active, into norite and hornblende peridotite. The argillaceous rocks all round the granite have been changed to mica-schists, while in a zone several hundred metres wide the alteration has gone still further, felspar being developed in the schists and quartzites, leading to the production of mica-gneiss as the extreme product of metamorphism. The limestone near the contact is silicified and full of wollastonite, epidote, plagioclase, garnet and hornblende. The proof of the modification of the granite by solution of limestone is complete. Wherever one finds a sheet of limestone enveloped by granite, it has a margin of hornblendic rocks which do not occur in any other situation. (*Fig.* 9.)

Lacroix holds that the granite rose into place in a slow, progressive manner by dissolution of the sediments which it replaced. Constantly, as the granite rose to higher and higher levels, it was preceded and accompanied by a " cortège d'émanations transformatrices," which reacted chemically with the sediments, so that the material which eventually passed into solution in the magma was no longer normal sedimentary rock, but rock which had already undergone extreme metamorphism under the influence of the emanation. The elements which were added to the contact rocks were especially alkalies and silica. Thus in the case of the mica schists, these were first " felspathized " by the emanation and converted into mica-gneiss, with a mineralogical composition not greatly different from that of the granite itself; consequently when the gneiss passed into solution in the granite, the only visible change in the latter was the development of some excess of biotite. It is otherwise with the limestone; no addition of alkalies and silica can transform this into anything resembling a normal granite, and the most characteristic minerals produced

FIG. 9. The granite massif of Quérigut, Pyrenees. (After A. Lacroix.)

by its alteration are hornblende and lime-felspar. It follows that solution of the contact metamorphosed limestone in the granite magma must profoundly modify the composition of the latter, the tendency being towards the production of hornblende diorite or gabbro.

There is an abundance of evidence connecting the amount of assimilation performed with the degree of metamorphism in the country rock. A good illustration is supplied by the granite massif of Bordères. On its north side this massif has exerted little metamorphic action; the schists are not felspathized and the limestone is not silicified. In this part the granite contains no hornblende and shows no basic modification. On the south side the contact metamorphism is intense; the granite is rich in hornblende and passes into a dioritic facies. This, of course, is to be expected, since the degree of metamorphism and the extent of solution are both dependent on the temperature of the magma at the time of intrusion, and on its richness in fugitive constituents.

Another area of the greatest importance for the study of assimilation and reaction at granite contacts is the Haliburton-Bancroft district of Ontario, which has been described by F. D. Adams and A. E. Barlow. In an area of 4,200 square miles, granite and granite-gneiss occupy 2,596 square miles, or about 62 per cent. The eruptive complex involves three distinct elements, as follows:—

(a) red granite or gneiss,
(b) gray granite or gneiss,
(c) amphibolite inclusions.

The first of these is essentially a rock composed of quartz, orthoclase and oligoclase, with very little biotite. The second is richer in dark minerals, and contains both ortho- and clino-pyroxenes as well as biotite and hornblende. The amphibolite inclusions form large masses of irregular shape, and also long narrow bands with distinct foliation; they range from masses occupying acres of ground to fragments of a few square inches. The constituent minerals are hornblende, which makes up about half of the rock, augite, ortho-pyroxene, labradorite, and a little pyrite and calcite. Other basic inclusions are rich in olivine and spinel. These amphibolite masses vary much in number from place to place, although they are seldom entirely absent. On the southern margin of the Glamorgan batholith they are reckoned to constitute about half of the entire rock. There is no

sharp line between granite with inclusions of amphibolite, and amphibolite cut up by veins of granite. All stages of the process can be observed whereby an immense solid mass of black amphibolite, absolutely free from any granitic admixture, is resolved into a swarm of amphibolite fragments distributed in a long stream through a body of mixed rock. While the detached masses often preserve their angular form, they sometimes seem to have been softened and rendered more or less plastic; and when this is the case, movements of the magma draw them out into long, narrow ribbon-like forms which, when pulled out very thin, pass into ill-defined gray streaks in the granite.

The amphibolites result in part from the intense alteration of limestone, every intermediate stage being represented between almost unaltered limestone, partly silicified limestone, and amphibolite with a little residual calcite. Fragments of unaltered limestone are very rare indeed within the granite mass, but some of the amphibolite inclusions show on close examination the presence of a core of unaltered carbonate. It is especially noteworthy that at this stage " the change is not one of solution or digestion of the limestone by the granite, for the fragments preserve their sharp and well-defined forms even when the alteration is complete." Such solution as actually takes place is *solution or incorporation of the amphibolitic and pyroxenic products that result from the alteration* of the limestone.

Adams and Barlow note that the products of the solution of amphibolite bear a marked resemblance to much of the " gray gneiss " which is widely distributed in the district. In some cases there seems to be a transition from the undoubted amphibolite inclusions into bands of gray gneiss, and " it is certain that in many places these streaks of gray gneiss represent inclusions of the amphibolite impregnated with gneissic material, and in a manner dissolved in the red gneiss." Adams and Barlow conclude, however, that " very strong evidence should be forthcoming before concluding that all the gray gneiss in the area is a product of the solution of amphibolite fragments in the red gneiss. Undisputed evidence of solution on such an extended scale has not as yet been obtained."

W. G. Foye shows that the conversion of limestone into amphibolite, as described by Adams and Barlow, involves a loss of 39 per cent. of lime and 42 per cent. of carbon dioxide from the limestone, and a gain of 48 per cent. of silica, 19 per cent. of alumina, 6.8 per cent. of ferrous oxide, 1.4 per cent. of magnesia,

4·5 per cent. of soda and 1·2 per cent. of potash by the limestone from the granite.

Another locality where there is quite convincing evidence of solution of limestone on a large scale is in the district of Sekukuniland, Transvaal. A pipe-like intrusion of foyaite (nepheline-syenite) three miles wide encloses a great block of limestone, having a visible area of half a square mile, which has been floated up by the magma through a vertical distance of three miles or perhaps more. Owing, one may suppose, to the complete and prolonged immersion of the limestone block in the magma, opportunity has been given for an intimate interaction to take place between them. When the foyaite is traced from the side of the pipe towards the central limestone mass, it is found to lose 15 per cent. of silica and 3 per cent. of ferric oxide, and to gain 10 per cent. of lime and 2 per cent. of magnesia (S. J. S.).

As a result of interaction with limestone, according to R. A. Daly and others, a magma may lose so much silica that it will give nepheline or leucite on cooling, instead of the usual alkali-felspars. Perfect illustrations of this effect are to be found at the granite-limestone contacts of Ontario, already described. The nepheline bearing rocks are developed either along the actual boundary between granite and limestone, or else in the limestone near the boundary. One of the smaller granite intrusions near Monmouth is about a mile wide; it has a continuous border of nepheline syenite from one-eighth to half a mile wide, and it is completely surrounded by limestone. Fine transverse sections are exposed right across the mass. Passing outwards from the centre, the granite gradually loses its quartz and passes into a syenite composed almost exclusively of felspar with only a little mica. This in turn becomes progressively richer in albite and dark minerals, and develops a little nepheline and corundum, so passing into the usual white or grey nepheline-syenite of the district. (This matter is discussed at greater length in Chapter XII.)

Conversely, a magma of such low acidity that nepheline or olivine would normally be formed by its freezing, may be so acidified by contact with siliceous country rocks that these minerals fail to develop in the neighbourhood of the contact. The nepheline-syenite of the island of Alnö, Sweden, is intrusive in gneiss, and towards the junction the syenite loses its nepheline and acquires biotite, while the gneiss loses its quartz and develops ægirine. There is thus a contact zone some three hundred metres

wide which is divisible, according to A. G. Högbom, into an outer belt of modified gneiss and an inner belt of modified syenite, with no sharp division between them. The nepheline syenite of Iivaara, Finland, also shows an acidified marginal zone, and so does that of Mariupol, Russia; while several cases have been described in Greenland. At Korok, for example, a syenitic rock containing nepheline and olivine loses both of these minerals and acquires quartz where it comes into contact with sandstone (N. V. Ussing). Similar evidence is available in the case of many olivine-bearing rocks; thus A. G. Högbom describes sills of olivine-dolerite at Nordingra, Sweden, which lose their olivine and become quartz-bearing near their contacts with granite and sandstone.

Remarkable evidence of reaction between magma and its walls is afforded by the corundum-bearing dykes of South Africa and the eastern United States. A. L. Du Toit describes dykes of aplite and pegmatite at Krantzkloof, Natal, which cut quartz-bearing schists and serpentine; in the schists they are normal quartz-felspar pegmatites, but when they enter the serpentine quartz disappears and its place is taken by corundum. The dykes are only a few feet wide, but each has a contact zone up to ten feet wide, consisting largely of the two minerals phlogopite (magnesian mica) and talc. The production of phlogopite from serpentine requires the addition of silica, alumina, potash and fluorine; that of talc requires the addition of silica to the serpentine.

The important corundum reefs of the Transvaal occur under similar conditions, and have been fully described by A. L. Hall. The country rock is invariably a highly magnesian type (serpentine, pyroxenite, peridotite, hornblendite) and where such rocks are cut by pegmatite reefs they have received an addition of silica, leading to the formation of talc; while the excess of alumina in the magma crystallised as corundum in the reefs. Entirely similar observations on the desilication of acid pegmatites by serpentine and peridotite, with production of corundum in the former and biotite, actinolite, and talc in the latter, have been made by S. G. Gordon in Massachusetts and elsewhere in the eastern United States.

We are now in a position to meet the question, whether deep magma exerts any solvent action on its containing walls, with the assurance that a certain amount of assimilation of country rock has unquestionably taken place in certain cases.

What it is that determines whether solution shall take place or not it is hard to say, but one may guess at the operation of several factors. The temperature of the magma at the time of intrusion is of outstanding importance, for before a cold solid can be dissolved in a hot liquid it must receive enough heat to bring it to the temperature of the liquid, and then a further amount to bring it into solution (heat of solution). Now, the only obvious supply of heat is that given up by the magma in cooling down from its intrusion-temperature to the temperature at which freezing sets in and increasing viscosity puts a stop to diffusion; so it is not the absolute temperature of the magma, but the degree of superheating that is important.

The composition of the wall rock in relation to that of the magma is also significant. F. Zirkel enunciated the rule that in acid magmas, acid enclosures are not dissolved, but basic ones are; in basic magmas, basic enclosures are not dissolved but acid ones are. This is a generalisation which certainly expresses in a rough way the result of many field observations, but it is no law. The apparent relation perhaps results from the fact that when an acid rock is dissolved in an acid magma, or a basic rock in a basic magma, the composition of the magma undergoes so little modification that the resulting rock shows no sign of contamination. H. H. Read reports that in Aberdeenshire the norite magma " appears to swallow up with avidity material of phyllitic nature, but to reject quartzose or calcareous rocks." The granites of the Onaping area, as described by W. H. Collins, have found the siliceous and argillaceous schists much more digestible than the ferruginous slates.

The concentration of the fugitive constituents in the magma, and the occurrence of conditions which facilitate or retard their escape into the country rock, have no doubt some influence in the matter. For instance, the reaction $CaCO_3 + SiO_2 \Longleftrightarrow CaSiO_3 + CO_2$ is reversible, and if the concentration of CO_2 in the magma is high enough, the silicification of a limestone in contact with that magma may be prevented. V. M. Goldschmidt ascribes the stability of calcite at the granite contacts of Rien, Norway, to the high partial pressure of CO_2. The granite of Bordères, in the Pyrenees, has reacted with limestone and schists on its south side, but not on the north. It seems possible that the facilities for the escape of fugitive bodies from the magma were greater on one side than the other, owing either to the structure of the country or to the inclination of the intrusive mass.

It should be remarked that the activity of fugitive constituents like water, carbon dioxide, and other acid gases, and the chlorides and fluorides of the metals, does not cease with the freezing of the silicate part of the magma, but they may continue to react with the country rock, and to transport mineral matter to and from the magma, and cause reactions and replacements, even down to atmospheric temperature.

There are many difficulties in the way of ascertaining the amount of solution that has taken place in any particular case; among these may be mentioned the inadequacy of the exposures; the obscuring effect of contact metamorphism, which we referred to earlier in this chapter; lack of information as to the initial composition of the magma, and so on. It has been pointed out by R. A. Daly that convection currents in the magma may sweep away the products of assimilation as quickly as they are formed, until the viscosity of the magma has become so great that neither convection nor assimilation is possible any longer; this may be the true explanation of the apparent absence of reaction at some contacts.

It is obvious that the amount of solution of cold country rock that a magma can effect by means of its internal heat alone is severely limited, for it depends on the amount by which the intrusion-temperature of the magma exceeds the temperature of active crystallisation. If, for example, the intrusion temperature of a magma were 900°, and it began to crystallise at 700°, then, since the specific heat of a liquid is in general a little higher than that of the same substance in the solid state, that body of magma, in cooling down from 900° to 700°, would supply just enough heat to bring about *a third of its own mass* of cold silicate rock up to the temperature of 700° and supply the necessary heat of solution to it. And further, this amount of solution could only be effected if there was no loss of heat at all to the surroundings, and if the conditions of mixing were perfect. For this reason, one should be very cautious about making or accepting statements regarding assimilation on a great scale, unless they are supported by incontrovertible evidence; and should fight shy of hypotheses which depend on the assumption of large-scale assimilation, unless the source of the necessary heat is indicated.

Magma which is only slightly superheated, or not superheated at all, is unable to take anything into solution unless energy is supplied by something else crystallising out; that is, the magma may take up something with which it is unsaturated by deposit-

ing something else with which it is saturated, the temperature remaining unchanged. Thus the addition of magnesian rocks to granitic magma will cause biotite to crystallise out; the addition of aluminous sediments to basaltic magma will induce deposition of anorthite. N. L. Bowen has discussed the possibilities that are opened up in this way, and he thinks that, although natural magma has little superheat, it may still be able to incorporate " considerable quantities " of foreign matter by reactive solution and precipitation.

The conclusion to which all this discussion leads is now clearly before us. It is that a body of deep magma can not be compared with the controlled systems that the chemist studies in the laboratory, for

(1) the magma can and does react with the containing walls during the whole period of its existence as a magma;
(2) not only does the magma gain matter from its walls, but it also gives up matter to the walls, notably silica, iron and alkalies, as well as water and acid gases;
(3) the concentration of the fugitive constituents of the magma is constantly changing, sometimes in one direction, sometimes in the other, so that there can be no permanent equilibrium between the solid and the fluid phases.

The realisation of these truths is an indispensable preparation for the discussion upon which we shall enter in the next chapter.

REFERENCES.

Adams, F. D. and Barlow, A. E.—Canada, Geol. Survey, Mem. 6, 1910.
Allen, E. T. and White, W. P.—Amer. Jour. Sci., 1906, *89*.
Amstütz, A.—Soc. Phys. Hist. Nat. Geneva, 1924, *142*.
Barrell, J.—U.S. Geol. Survey, Prof. Paper 57, 1907.
Bastin, E. S.—U.S. Geol. Survey, Bull. 445, 1911.
Bowen, N. L.—Amer. Jour. Sci., 1912, *551*.
do. —Jour. Geol., 1922, *513*.
Brögger, W. C.—Eruptivgesteine des Kristianiagebietes, vol. II., *147*.
Brouwer, H. A.—Centralblatt Min., 1918, *41*.
Busz, K.—Geol. Mag., 1896, *492*.
Clarke, F. W.—U.S. Geol. Survey, Bull. 770, 1924.
Collins, W. H.—Canada, Geol. Survey, Mem. 95, 1917.
Daly, R. A.—Bull. Geol. Soc. Amer., 1910, *87*.
do. —Jour. Geol. 1918, *97*.
Day, A. L. and Allen, E. T.—Carnegie Inst. Washington, Publ. 360, 1925.

Day, A. L. and Shepherd, E. S.—Bull. Geol. Soc. Amer., 1913, *573*.
Du Toit, A. L.—Trans. Geol. Soc. S. Africa, 1919, *53*.
Eskola, P.—Jour. Geol., 1922, *265*.
Fenner, C. L.—(Quartz-tridymite) Amer. Jour. Sci., 1913, *331*.
do. —(assimilation) Jour. Geol., 1914, *594*, *694*.
Foye, W. G.—Amer. Jour. Sci., 1915; *413*.
Friedländer, J.—Zeit. Vulkanologie, 1917, *210*.
Goldschmidt, V. M.—(Contact) Videns.-Selsk. Skrifter, 1912, no. 22.
do. —(Spitzbergen) ditto 1911, no. 9.
Gordon, S. G.—Proc. Acad. Nat. Sci. Philadelphia, 1921, *169*.
Hall, A. L.—S. Africa, Geol. Survey, Mem. 15, 1920.
Harker, A.—Quart. Jour. Geol. Soc., 1895, *125*.
Högbom, A. G.—(Alnö) Sveriges Geol. Undersökning, no. 148, 1895.
do. —(Nordingra) Geol. Föreningens Förhandl., 1909, *347*.
do. —(Ragunda) Sveriges Geol. Undersökning, no. 182, 1899.
do. do. Bull. Geol. Inst. Univ. Upsala, 1910.
Holden, E. F.—American Mineralogist, 1924.
Jaggar, T. A.—Amer. Jour. Sci., 1917, *161*.
Königsberger, J.—Neues Jahrbuch Min., B.B.32, 1911, *32*.
Lacroix, A.—Carte geol. de la France, Bull. 64 and 71, 1898-1900.
Leith, C. K. and Harder, F. C.—U.S. Geol. Survey, Bull. 338, 1908
Mennell, F. P.—Geol. Mag., 1911, *10*.
Miller, W. J.—Bull. Geol. Soc. Amer., 1914, *258*.
Pirsson, L. V.—Amer. Jour. Sci., 1897, *421*.
do. —U.S. Geol. Survey, 20 Ann. Rep. 1899, *257*.
Read, H. H.—Scotland Geol. Survey (Geology of Huntly, etc.), 1923.
Shand, S. J.—Trans. Geol. Soc. S. Africa, 1921, *111*.
Sigmund, A.—Tschermaks Min. Pet. Mitth., 1898.
Sollas, W. J.—Trans. Roy. Irish Acad., 1894, *477*.
Sosman, R. B. and Merwin, H. E.—Jour. Washington Acad. Sci., 1923, *389*.
Thomas, H. H.—Quart. Jour. Geol. Soc., 1922, *229*.
Tyrrell, G. W.—Geol. Mag., 1916, *193*.
Ussing, N. V.—Meddelelser om Grönland, Copenhagen, 1912.
Wright, C. W.—U.S. Geol. Survey, Prof. Paper 87, 1915.
Wright, F. E. and Larsen, E. S.—Amer. Jour. Sci., 1909, *421*.
Zirkel, F.—Lehrbuch der Petrographie, vol. I., 1893, *599*.

CHAPTER V.

THE FREEZING OF THE MAGMA.

When a liquid freezes, it may give either a mass of crystals or a glass. In the first case there is an abrupt change of all the physical properties of the system, such as viscosity, density, refractive index, and specific heat, at the freezing point. In the second case there is only a gradual increase in the viscosity of the liquid, until it becomes so great that we think of the system as a solid, accompanied by small progressive changes in the other properties; there is no definite freezing point at all. The factors which determine whether any liquid shall crystallise or become a glass are principally the fluidity of the liquid and the rate of cooling; other things being equal, slow cooling favours crystallisation and high viscosity retards it. Since the gases and simple salts dissolved in a magma increase its fluidity, a high concentration of fugitive constituents will favour crystallisation; and there is reason to believe that the glassy character of certain lavas is due more to the loss of their gases than to rapid cooling.

Freezing with production of glass introduces nothing new, for glass is just a more viscous liquid; but crystallisation involves the appearance of new solid phases, and the course of crystallisation and the nature of the products are subject to laws which we must study.

A pure substance such as mercury or water has a perfectly definite freezing point (at a given pressure); above the freezing temperature only the liquid form can exist, below it only the solid form is stable. Under a fixed pressure, there is only one temperature at which the solid and the liquid can exist in contact, and that is the freezing point. If we ever had to deal with a magma consisting of molecules of one kind only, say a pure anorthite magma, we should expect it to crystallise at 1550° precisely (under atmospheric pressure), while a pure diopside magma should crystallise at 1390°. Such a magma is probably never realised in nature. Many rocks are known which consist almost entirely of one mineral, but small amounts of other minerals are seldom absent, and, in addition, we have seen that certain fugitive

constituents are probably present in every magma. Most rocks contain from four to ten or more distinct minerals, and when some of these are complex solid solutions, like hornblende and augite, the number of simple silicate molecules in the magma must be large.

Now a liquid mixture with two or more components behaves quite differently, in the act of freezing, from a liquid of simple composition. The difference is shown in the following ways :—

(1) The temperature at which freezing begins is not the same as the freezing point of any one of the components, and is different even in different mixtures of the same components.

(2) Freezing does not take place entirely at one temperature, but continues through a certain range of temperature. That is, instead of a freezing point there is a freezing interval.

(3) The crystals that form first do not have the same composition as the liquid out of which they crystallised. In different mixtures of the same components, the crystals that form first may be different.

The first point is just a re-statement of the Raoult-Blagden Law (page 47) that every substance when dissolved in a liquid capable of crystallising, lowers its freezing point. Sea water has a lower freezing point than fresh water on account of the small quantity of salt dissolved in it, and by increasing the concentration of salt the freezing point can be brought down to —23°. In a mixture of molten silicates there is no distinction of solvent and dissolved substance, but each component may be considered to be dissolved in the others.

The freezing of the system anorthite-diopside has been studied by N. L. Bowen. The melting or freezing point of pure anorthite is 1550°, that of diopside is 1390°, but a mixture containing anorthite 80 parts, diopside 20 parts, only begins to freeze at 1485°, and is not completely solid till 1270° is reached. A mixture of diopside 80 parts, anorthite 20 parts, begins to freeze at 1350°, and the last trace of liquid only disappears at 1270°. Each of these mixtures has therefore a freezing interval instead of a single freezing point, which illustrates the second of the above statements. But the mixture which contains 58 parts of diopside to 42 parts of anorthite does not even begin to freeze until 1270° is reached, and then crystallises completely at that temperature. This particular mixture of diopside and anorthite

has the lowest possible freezing point, and is called the *eutectic mixture* of these two components. Observe that a eutectic mixture resembles a pure substance in having a definite freezing point.

The third point is easily verified by referring again to salt and water. It is well-known that when sea-water freezes, the ice that forms is entirely free from salt; on the other hand, that if concentrated brine is cooled down, it deposits pure salt at first. The solution that contains exactly 23.5 per cent. of salt (the eutectic mixture) deposits ice and salt simultaneously. A silicate melt behaves in a similar way, as the following table shows :—

Mixtures of diopside and anorthite.

I.	II.	III.
Mixtures with more than 58% of diopside.	*Mixture of 58 parts diopside, 42 parts anorthite.*	*Mixtures with more than 42% of anorthite.*
Diopside crystallises first and continues to form until the eutectic temperature (1270°) is reached ; then diopside and anorthite crystallise together in eutectic proportions.	This mixture remains fluid until the eutectic temperature (1270°) is reached ; then it gives crystals of both minerals in the above proportion of 58 to 42.	Anorthite crystallises first and continues to form until the eutectic temperature (1270°) is reached ; then anorthite and diopside crystallise together in eutectic proportions.

We may put these observations in the form of a rule of general application, as follows: Any mixture which contains one component in excess of the eutectic proportion will deposit that excess as it cools, until the remaining liquid has the eutectic composition, when the mixture will freeze as a whole.

The precise composition of the eutectic mixture of any two substances can only be found by experiment, but it is roughly true that the eutectic mixture holds more of the component of lower melting point, and the greater the difference between the melting points of the two components, the more of the more fusible component appears in the eutectic.

It is much easier to demonstrate these relations graphically than verbally. In *Fig.* 10 the composition of all possible mixtures of diopside and anorthite is plotted on the base line, while temperature is recorded vertically. When the initial freezing points of various mixtures are inserted in the diagram, they are found to lie on two curves, AE and DE, which start from the melting points of the pure components and meet at the eutectic point E, corresponding to the composition diopside 58, anorthite 42, and to the temperature 1270°. This diagram therefore contains complete information about the crystallisation of all possible mixtures of diopside and anorthite.

Every extra component that is added to such a mixture causes a further lowering of the freezing point, the new minimum corresponding to a ternary, quaternary, or higher eutectic mixture. Thus in the system silica-anorthite-wollastonite, which has been studied by G. A. Rankin (*Fig.* 11) there are three binary eutectics crystallising at 1436°, 1359°, and 1299° respectively, and a ternary eutectic, composed of 40 parts of anorthite, 32 of wollastonite, and 28 of tridymite, which freezes at 1165°. In the freezing of a ternary mixture, we may say loosely that the component which is in greatest excess, as compared with the composition of the ternary eutectic, will crystallise first; then the component which is next in excess, along with the former one; then the ternary eutectic of all three components. Thus in a

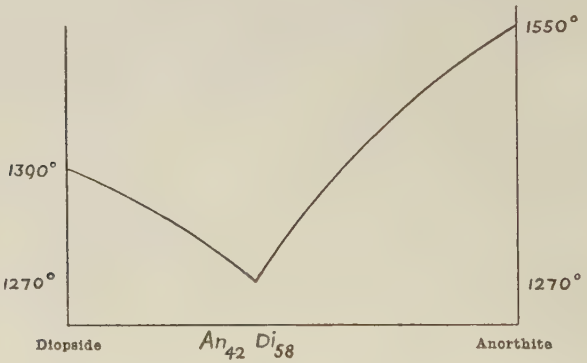

FIG. 10. The binary system diopside-anorthite. (N. L. Bowen.)

poly-component mixture there is a sequence of crystallisation of the following type :—

A ; A + B ; A + B + C ; A + B + C + D, etc.,

always ending with a multiple eutectic of all the components.

The graphical representation of the freezing of such a system becomes very difficult as the number of components increases. For a ternary system one uses a triangular diagram in which the percentage of each component is measured from 100, at an apex of the triangle, to zero at the opposite side. Thus in *Fig.* 11 the point E corresponds to the composition anorthite 40, wollastonite 32, tridymite 28, which is that of the ternary eutectic of these components. A point on one of the sides of the triangle obviously represents a mixture containing only two of the components. The lines that join the ternary eutectic point to the three binary points cut the triangle up into three fields, one of

which encloses all mixtures from which anorthite crystallises first, another those from which wollastonite crystallises first, and a third those from which silica crystallises first. It is to be noted that the latter field is itself divided by a line which corresponds to the temperature of 1470°. Mixtures which are very rich in silica begin their crystallisation above 1470°, so the silica crystallises as cristobalite; when the temperature of crystallisation is below 1470°, tridymite appears instead. The directions of falling temperature are indicated by arrows, the temperature co-ordinate being supposed to stand at right angles to the plane of the paper.

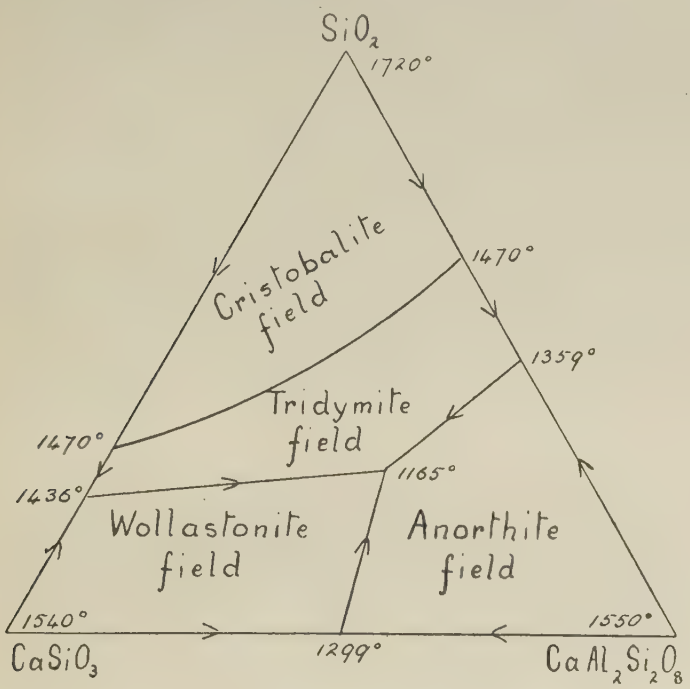

FIG. 11. The ternary system anorthite-wollastonite-silica. (After G. A. Rankin.)

Everything that has been said so far refers to systems in which neither combination nor solid solution takes place between the components. Among rock-forming minerals, however, solid solution is very common, as we saw in Chapter II., and certain chemical combinations are also possible. Either of these occurrences will change the course of crystallisation completely.

If the components of a mixture are capable of forming solid solutions, the eutectic relation disappears, for the crystals formed

at any temperature always hold some of each component. The composition of the crystals is in general different from that of the liquid, so the freezing diagram shows two curves, one (called the liquidus) containing the initial freezing points of all possible solutions of the two components, and the other (the solidus) representing the composition of the crystals formed at these freezing points. Figure 12 is N. L. Bowen's diagram to illustrate the formation of the plagioclase felspars.

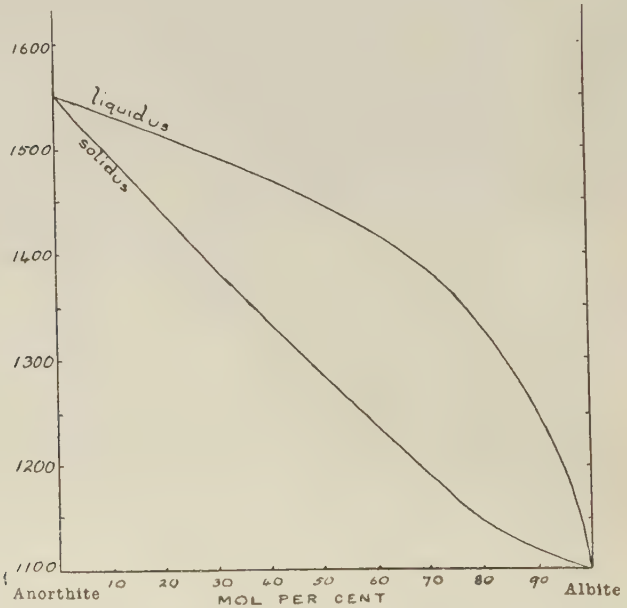

FIG. 12. The melting and freezing curves of the plagioclase felspars. (N. L. Bowen.)

What happens in the freezing of a plagioclase melt may be deduced from the diagram. A melt of the composition Ab_1An_2 begins to freeze at 1490°, but the composition of the solid phase is $Ab_{12}An_{88}$. Thus the remaining liquid is enriched with albite, and as cooling proceeds the composition of the liquid changes steadily, along the course indicated by the liquidus, towards the albite end of the diagram. The crystals meanwhile continue to grow by the addition of layers of felspar which are progressively richer and richer in albite, and the last layer will be nearly pure albite.

If a third component is added to the albite-anorthite system, it may form a binary eutectic with each of these substances, but there can be no ternary eutectic. A freezing diagram for the

system quartz-albite-anorthite is reproduced in *Fig.* 13, after J. H. L. Vogt. It shows only two fields, one in which silica crystallises first, and another in which plagioclase of variable composition crystallises first. Studying the direction of the temperature arrows, it will be seen that the crystallisation of this system tends to proceed towards the quartz-albite eutectic.

A different kind of complication arises when two of the components are capable of reacting together as the temperature falls.

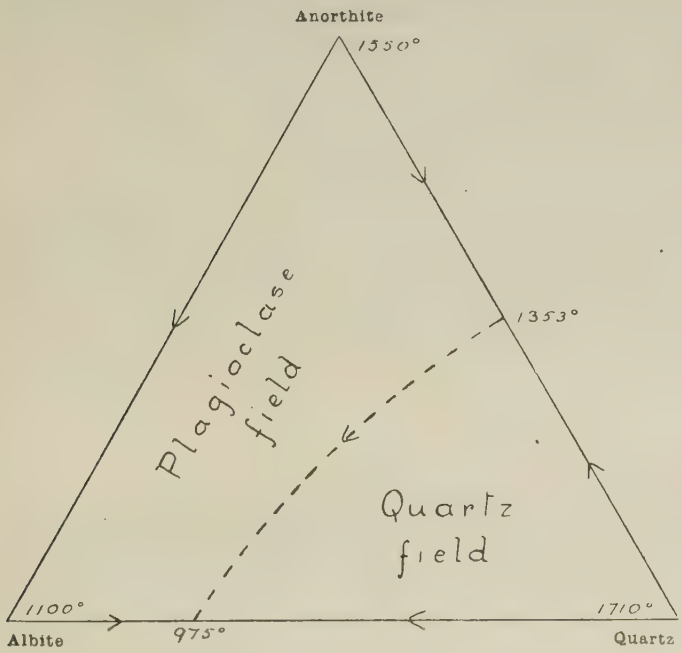

FIG. 13. The system plagioclase-quartz. (J. H. L. Vogt.)

Thus Bowen and Andersen showed that forsterite (magnesian olivine, Mg_2SiO_4) is stable in presence of free silica above the temperature of 1557°, but below that temperature the two substances combine to form clino-enstatite. There is consequently no eutectic between forsterite and silica, but only one between clino-enstatite and silica. Morey and Bowen showed that melts of leucite and silica behave in the same way, leucite crystallising out above 1170° and orthoclase below that temperature; there is no eutectic between leucite and silica, but only one between

orthoclase and silica. Thus from a fluid rich in the constituents of enstatite, olivine will generally crystallise first, and later, when the temperature has fallen sufficiently, it will react with the remaining liquid to form enstatite. Or from a melt rich in the constituents of orthoclase, leucite will crystallise first, afterwards reacting with the liquid to form orthoclase.

As the number of components increases, the difficulty of working out the course of crystallisation, by experimental methods, becomes very great. But it is certain that the conclusions which have been derived from the study of simple systems must apply to more complicated ones too; and even though it should never be possible to imitate in the laboratory the crystallisation of an extremely complex system such as a natural magma, yet the study of the simple systems of silicates and oxides will continue to throw light on the larger problem. The chief difficulty that presents itself, when one tries to institute comparisons between the results obtained in the laboratory and those seen in nature, arises out of our uncertainty regarding the physical conditions that prevailed in the magma chamber during crystallisation. Not one of the controlling conditions, temperature, pressure, or concentration, is fully known; and we may not even assume that these conditions remained constant, or that they varied in a regular and deducible way, during the freezing of the system. What the effect of varying physical conditions may be, we can judge from a few simple considerations.

The effect of variable pressure. The influence of pressure on the freezing points of liquids is expressed by the Law of Le Chatelier. When crystallisation takes place with reduction of volume, the freezing point is raised by pressure; when crystallisation takes place with increase of volume, the freezing point is lowered by pressure. Thus water, which expands in freezing, has its freezing point lowered about 10° by a pressure of 1000 atmospheres. Johnston and Adams give the following data for metals:—

Tin	+3.28°	per	1000	atmospheres
Cadmium	+6.29°	,,	,,	,,
Lead	+8.03°	,,	,,	,,
Bismuth	—3.55°	,,	,,	,,

Little is known about the behaviour of silicates in freezing, but it is believed that most of them contract. Several crystallised silicates are known to be denser than their glasses, and at least

one eruptive rock (the diabase of the Palisades, New Jersey) has been shown to be denser than its melt. J. H. L. Vogt estimates that the rise in the freezing points of silicates under pressure is about 5° per 1000 atmospheres. J. Johnston contrasts the influence of pressure and temperature upon physical equilibria in the following terms :—

(1) In systems without a vapour phase, a change of pressure of 1000 atmospheres will in general effect no more than a change of temperature of 10°.

(2) The effect of pressure upon viscosity and similar factors is in general insignificant as compared with the effect of temperature.

(3) Solubility is affected only slightly by change of pressure, so slightly that the effect is negligible as compared with that of change of temperature.

Nevertheless, we have to reckon with the fact that all the physical constants of the magma, including eutectic temperatures and concentrations, are affected by change of pressure, so there is a real difficulty about applying to deep magma the results determined by experiment at atmospheric pressure. The large size of the crystals of early consolidation (quartz, felspar, leucite, olivine) in many lavas and dyke-rocks, as well as the signs of corrosion which these crystals sometimes show, have both been ascribed in the past to changes of pressure accompanying the rise of magma from the depths.

High pressure also favours the production of minerals of small molecular volume. It has been maintained by L. L. Fermor that garnet, for instance, is a "high pressure" mineral, and that underneath the familiar plutonic rocks in the crust there is a zone of garnet-bearing rocks, of which the basic members are eclogites (garnet-pyroxene rocks) and the acid members garnetiferous granites. If these rocks are brought up to higher levels, it is supposed that they will transform into normal plutonic types. Fermor suggests that meteorites are fragments of rocks derived from the infra-plutonic zone of some dissipated celestial body, and that the chondrules represent garnets which have melted and recrystallised owing to the reduction of pressure. J. W. Evans accepts Fermor's theory and adds zoisite, epidote, kyanite, muscovite and biotite to the list of minerals likely to be formed under infra-plutonic conditions.

One is thus compelled to take into consideration the possibility that new phases may appear, and earlier phases be resorbed

or transformed, solely in consequence of variation of pressure in the magma chamber.

The effect of variable temperature. The cooling of a body of deep magma, especially if it is enclosed in a chamber which has no outlet to the surface of the earth, is likely to proceed with great regularity; but this does not apply to magma which is brought suddenly into contact with cold rocks, or rushed quickly up to the surface through a volcanic pipe. In these cases, a period of slow cooling is followed by one of rapid cooling. This will tend to yield a rock with porphyritic texture, since the earlier crystals will be large and the later ones small, or the groundmass

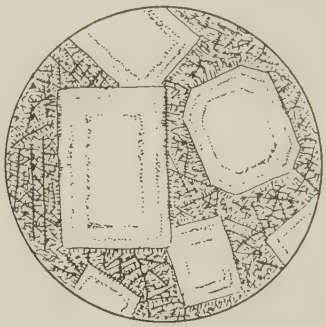

FIG. 14. Melilite crystals enclosing two successive generations of magnetite grains and embedded in a groundmass of magnetite, melilite and fayalite. (After J. H. L. Vogt.)

may even be glassy. Too rapid cooling may also lead to the preservation of unstable phases. For example, a magma rich in magnesium silicates may give olivine crystals during the earlier period of cooling (see p. 80), and if it is then chilled quickly, the normal reaction of olivine with silica to form ortho-pyroxene may be prevented or left incomplete; the resulting rock will therefore hold crystals of olivine in a highly siliceous base. Such rocks have been described repeatedly, but it is clear that they represent systems in which equilibrium has not been reached.

In the case of magma that is rushed quickly to the surface, the normal fall of temperature may be interrupted by a sharp rise, owing partly to reactions taking place between the escaping gases, partly to oxidation of iron compounds, and partly to latent heat developed during the sudden onset of crystallisation which

must ensue when the escape of gases causes the freezing point of the magma to rise. G. Tammann has described an experiment in which a sodium silicate glass was warmed up to about 500°, whereupon crystallisation set in with such rapidity that the whole mass was raised to red heat by the latent energy set free.

Effects that may not unreasonably be ascribed to such fluctuations of temperature are, for example, the corrosion and resolution of early formed crystals, such as those of quartz in many lavas; the transformation of amphibole or garnet into pyroxene; and the reversal of the usual order of zoning in plagioclase crystals. There may even be an oscillatory recurrence of crystallisation between two or more phases. *Fig.* 14 (after J. H. L. Vogt) shows crystals of melilite enclosing two successive zones of magnetite grains and surrounded by still another generation of magnetite.

The effect of variable concentration. The variations which we have to discuss under this heading may affect either the fixed or the fugitive components of the magma. As regards the former, we have seen that a certain amount of assimilation of country rock undoubtedly takes place in some magma chambers, if not in all. Whether the foreign material is actually taken into solution, or whether it is merely worked over by the magma and transformed into something else, as quartz grains in lava are changed into augite or zeolites, still the process represents a departure from the normal course of crystallisation, and it often leads to the appearance of entirely new phases. The formation of melanite garnet in syenitic rocks, for example, appears to be a direct consequence of the contamination of the magma with lime, for melanite is never found except in the neighbourhood of limestone contacts; and there is strong reason to suspect that assimilation of limestone is the cause of the appearance of melilite too. The incorporation of aluminous sediments, on the other hand, may induce the crystallisation of andalusite, cordierite, almandine, or corundum. In all such cases it is clear that the composition of the liquid phase was subject to irregular and unknown variations during the course of freezing.

H. A. Miers has pointed out that if supersaturation plays a part in the freezing of rock magma, then the inoculation of the magma with foreign grains may affect the sequence of crystallisation. For example, the separation of quartz from a siliceous magma may be accelerated by the presence of foreign quartz

grains, while in the absence of these the same magma may leave a residue of uncrystallised siliceous glass. J. H. L. Vogt states that supersaturation plays an important part in artificial melts, and it may well do so in lava too, in which case inoculation might have the effect that Miers describes.

Variations in the concentration of the liquid phase, during the crystallisation of magma, may be brought about by the sinking or rising of the early-formed crystals from the zone in which they originated to deeper or higher levels, where, owing to differences of pressure or temperature, they are redissolved. The sinking of heavy minerals like olivine and magnetite has actually been demonstrated both in the field and in the crucible, but the resolution of the precipitated crystals at lower levels still awaits demonstration. But wherever gravitational separation of phases has taken place, it must follow that the rocks formed do not accurately represent the composition of the magma from which they were developed, and do not clearly indicate the equilibria which obtained in that magma as a whole.

The escape of fugitive constituents from the magma during freezing must have a marked effect upon the course of crystallisation. So long as these constituents are retained in the liquid phase, no complication is introduced by their presence, but it is certain that in many cases they make their escape while freezing is actually going on. Great volumes of gas are emitted from volcanic vents and fumaroles, and from the surface of flowing lava. Most rocks in the earth-crust are more or less porous, and the phenomena of contact metamorphism show how easily gases and solutions can pass through the walls of the magma chamber. But the progressive loss of these components during the process of crystallisation must affect all equilibria and all equilibrium temperatures in the system.

At the beginning of freezing, one has only to reckon with the escape of fugitives from the outer and upper parts of the magma; but after these parts have become nearly or completely solid, they must act as media for the escape of solutions or gases from the still liquid interior. The solid phases may now be modified by reaction with the escaping fluids. Under such conditions, felspar and biotite are replaced by tourmaline, topaz and white mica; augite is transformed into hornblende and biotite; soda-pyroxenes or soda-amphiboles make their appearance in the rock; plagioclase felspars are albitized or mantled with anorthoclase; and sulphidic ores are introduced.

It is likely that future study of the order of crystallisation in eruptive rocks, and of departures from the accepted order, will emphasise more and more the effect of changes in the concentration of the fugitive components of the magma during freezing.

It follows, from the facts brought out in this discussion, that magma is not by any means directly comparable to an artificial melt in a crucible. In the first place we are ignorant of the precise composition of the magma, both on account of the loss of fugitive components during freezing, and because some separation of the heavier from the lighter phases may have taken place under the influence of gravity. In addition, we do not know what fluctuations of temperature, pressure, and concentration have occurred in the system while freezing was going on. It may be anticipated that comparison with artificial systems will be easier in the case of surface magma than in that of deep magma, for then the pressure is known, the temperature is measurable, and the concentration of the fugitive components diminishes rapidly as soon as the pressure falls to that of the atmosphere.

If, then, aware of all these difficulties, we turn to the eruptive rocks and attempt to deduce from them the sequence of events in the freezing of the magma, we find that there are practically only three rules for our guidance, namely

(1) When one crystal encloses another, the latter must be of earlier formation;

(2) The earlier crystals will generally be well shaped, the later ones less so owing to their mutual interference;

(3) When the same mineral occurs both in large and in small crystals, it is to be presumed that the large crystals started to grow first.

But straightforward as these rules seem, they are not wholly reliable, as the following cases show. In some experiments on synthetic lavas, Fouqué and Michel-Lévy observed that leucite crystals were formed which held enclosures of glass, and that this glass subsequently crystallised and formed minute augite crystals within the leucite. J. Morozewicz has described synthetic cordierite crystals with glass enclosures which, on continued heating, deposited magnetite crystals within the host. In either of these cases, the application of rule 1 would lead to the wrong conclusion as to the order of crystallisation. F. Walker has found olivine crystals enclosing small crystals of augite, and has shown that the augite is the younger of the two

minerals, the magma having made its way along cracks in the olivine crystals and crystallised there as augite and felspar. G. P. Merrill, too, observed augite growing along cracks in olivine crystals.

N. L. Bowen points out that it depends entirely on the direction in which a rock-section happens to be cut, whether an enclosure seems to lie at the centre or near the margin of the host. An enclosed crystal may appear in the centre of the section, yet it may have lain only just within the margin of the host. In such a case it is possible that the core of the host crystallised before the enclosed crystal, and the mantle afterwards; thus the apparent order of crystallisation, as judged by enclosures, is really the order of completion of crystallisation, not that of beginning of crystallisation as it is usually held to be.

The second rule is also doubtfully reliable, for some minerals, such as garnet and staurolite, are able to form well-shaped crystals even when they grow in a solid matrix; this is shown by the appearance of perfect crystals of these minerals in metamorphic rocks which have been recrystallised without melting. J. F. N. Green has described the formation of garnets in metamorphosed lavas and tuffs in the Lake District of England, many of which are perfect rhombic dodecahedrons, although they grew in a solid medium. In the slates surrounding certain granite masses there are large crystals of felspar, which are indistinguishable from those in the granite itself; apparently these crystals grew in a solid matrix, pushing the other grains aside to make room for themselves. On the other hand, a mineral which lacks crystal outlines was not necessarily formed at a late stage, for crystals of early formation, such as quartz and olivine crystals in certain lavas, are often partly resorbed at a later stage in the cooling process, and so become rounded.

As regards the third rule, when one constituent such as felspar occurs in enormous crystals, which are embedded in a fine-grained crystalline matrix, one naturally concludes that the large crystals started to grow long before the little ones. But felspar crystals of the largest size in granites and syenites are often full of minute enclosures of the other minerals right to the centre. The big leucite crystals in the lavas of the Eifel district of Germany often enclose grains of every other mineral that is associated with them. In these cases the third rule and the first lead to different conclusions.

It is such difficulties and contradictions as these that give force

to J. H. L. Vogt's remark that " many of the petrographical contentions about the order of crystallisation in igneous rocks are partly questionable and partly wrong." The contentions to which Vogt takes exception are those that are embodied in the Rosenbusch Rule, according to which the normal order of crystallisation in eruptive rocks is as follows :—

(1) Accessory minerals, such as zircon, xenotime, apatite, magnetite, chromite, sphene : or more generally those constituents which are present in smallest quantity ;

(2) Ferromagnesian minerals, orthosilicates such as olivine and biotite preceding metasilicates, and ortho-pyroxene preceding clino-pyroxene ;

(3) Felspars and other alkaline silicates, the lime felspars first ;

(4) Quartz, and any glassy residue.

It must be said at once that the great petrographer whose name is associated with the rule was fully aware that his rule is one with many exceptions ; the question before us is whether the exceptions are important enough to invalidate the rule. It will be seen that the very first section of the rule appears to contradict the laws of solution, for the components that are present in least amount ought to be among the last to crystallise. But when, in a granite, one sees minute crystals of zircon, xenotime or allanite enclosed in biotite, and little biotite scales enclosed in orthoclase, what conclusion can one draw except that the zircon crystallised first, then the biotite, and lastly the felspar? It is true that if the minerals had all crystallised *at the same time,* then the large and abundant felspar crystals would be almost certain to enclose some of the smaller biotites and zircons ; but then it is almost as unlikely, on theoretical grounds, that the minerals should all have crystallised at the same time as it is that zircon should have crystallised first.

The strange contradiction now appears, that whenever the proportion of an accessory mineral such as zircon rises to a higher value than usual, then that mineral appears to have crystallised at a later stage than usual. So in a nepheline rock occurring at Mariupol, Russia, which contains about 2 per cent. of zircon, that mineral has enclosed albite and ægirine. According to J. Morozewicz, the order of beginning of crystallisation in this rock was albite, ægirine, zircon, nepheline ; and the order of completion of crystallisation was zircon, nepheline, ægirine, albite. Late crystallisation of zircon has also been

noticed in the zircon-syenites of Norway, and the writer has observed it in a dyke rock in South West Africa; in each case the rock is unusually rich in zircon.

Sphene, like zircon, is often present in more than the average quantity in syenites and foyaites. A dyke-foyaite in Assynt, Scotland, which was described by J. Horne and J. J. H. Teall, contains much sphene, which has crystallised in skeleton plates, enclosing orthoclase, nepheline, and pyroxene. (*Fig.* 15.) P. Geijer observed similar crystals of sphene in syenite at Kiruna, Lapland. F. H. Hatch has recorded orthoclase crystals enclosed

FIG. 15. Skeleton crystal of sphene (dotted) enclosing pyroxene (P), othoclase and nepheline; Assynt, Scotland. (After J. J. H. Teall.) Magnification 28.

in sphene in Madagascar, and F. M. Berwerth observed plagioclase in sphene at Ditro, Hungary. Pyroxene enclosed in sphene has also been noticed in Brazil (Machado) and Finland (Ramsay and Berghell).

Apatite also shows such anomalies. Enclosures of plagioclase in apatite have been noted by von Chrustchoff in Volhynia, by Lacroix in Madagascar, and by Hansel at Mount Vesuvius. Hornblende is enclosed by apatite in Bulgaria, according to Dimitrow; and J. P. Iddings notes the crystallisation of apatite after augite and olivine in Wyoming. W. S. Bayley figures skeleton crystals of apatite from a diabase in Minnesota, and

P. A. Wagner has figured similar skeleton crystals from "blue ground" at Kimberley, in which apatite is one of the last minerals to crystallise. (*Fig.* 16.)

The lime-iron garnet, melanite or andradite, is an accessory constituent of many syenitic rocks, and it frequently crystallises at a very late stage. C. W. Drysdale mentions an augite syenite at Franklin, British Columbia, with less than one per cent. of melanite, which has crystallised after biotite, hornblende and diopside. Still later crystallisation of this mineral has occurred in Finland, where it follows nepheline (V. Hackmann); and the

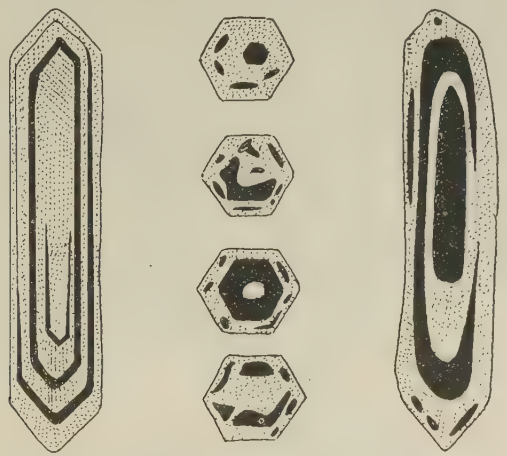

FIG. 16. Skeleton crystals of apatite from kimberlite; Kimberley. (After P. A. Wagner.)

writer has described cases of very late formation of melanite in Scotland and in the Transvaal. (*Fig.* 17.)

Even the oxides crystallise late at times. W. C. Brögger records the occurrence of nepheline in magnetite in Norway, and Streng found that, in certain dolerites of Germany, magnetite had crystallised after plagioclase and olivine. Ilmenite sometimes encloses orthoclase; and even chromite, which, as a rule, precedes olivine, has been observed to be moulded on olivine crystals in the island of Rum (A. Harker).

When we come to the second section of the Rosenbusch rule, the exceptions are no less numerous. It has always been recognised that plagioclase crystallises before augite in many dolerites

and basalts, though not in all. Streng's observations on the basalts of Giessen, Germany, illustrate this point very clearly. These rocks contain plagioclase, augite and olivine, and the upper levels of the flows are partly glassy. In the more light coloured facies, there are crystals of plagioclase and olivine in a glassy base which retains the augite; while in the darker facies the

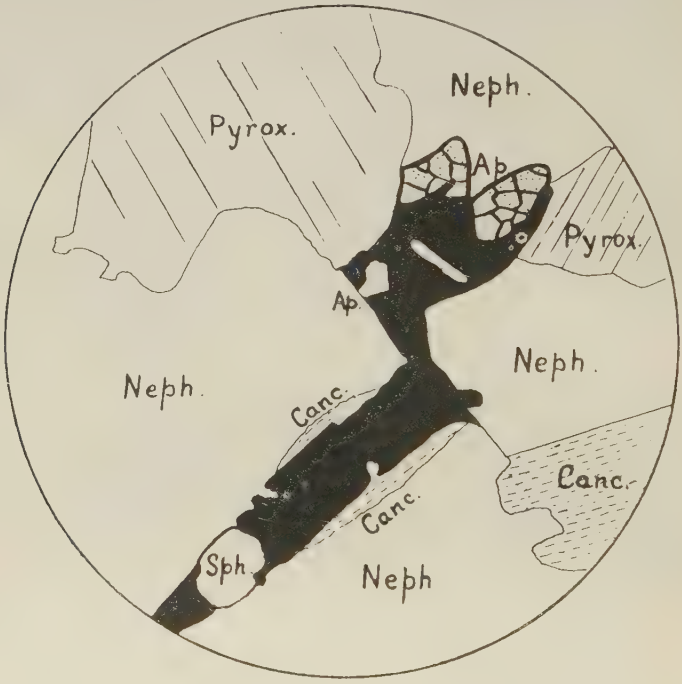

Fig. 17. Melanite (black) with pyroxene, nepheline, apatite, sphene and cancrinite. The melanite is interstitial to all constituents except cancrinite. Magnification 20. Sekukuniland, Transvaal.

crystals are of augite and olivine, and it is the felspar which is retained in the glass.

A. Harker showed that among the anorthite-olivine rocks in the island of Rum, Scotland, those varieties which hold much olivine have that mineral crystallising first; the anorthite rich varieties show anorthite crystallising first; and some rocks of intermediate composition show the two minerals to have crystallised simultaneously. (*Fig.* 18.) Crystallisation of olivine after

plagioclase has also been observed by Chrustchoff in Volhynia and by Hansel at Mt. Vesuvius. Augite enclosed in olivine was noted by W. G. Foye, in Honduras, and hypersthene in olivine by G. W. Williams in Maryland. The simultaneous crystallisation of plagioclase and hypersthene is recorded by J. P. Iddings, in Oregon; while E. V. Shannon has described graphic intergrowths of augite and plagioclase in Massachusetts. It is well known, too, that soda-pyroxenes and soda-amphiboles may either precede or follow the felspar and quartz in alkaline granites.

FIG. 18. Olivine crystals enclosing and moulded upon anorthite; island of Rum. (After A. Harker.) Magnification 20.

With the third clause of the Rosenbusch rule, so far as it can be considered apart from the preceding ones, there is less fault to be found. The crystallisation of lime-rich plagioclase before soda-rich plagioclase is a necessary consequence of the course of the freezing curves (page 78 and *Fig.* 12). But even here we meet occasional reversals of the rule, as in the Rapakiwi granites of Sweden and Finland, where the large orthoclase crystals have mantles of oligoclase around them. To explain this unusual feature it has been assumed that the orthoclase crystals, after growing to a certain size, sank, or by some other means came into a layer of magma in which the crystallisation of plagioclase had not been completed, and there received their mantles. J. E. Hibsch has described large plagioclase crystals in basalts of the central Caucasus, which show a core of the composition $Ab_1 An_1$, followed by a sharply defined outer zone, of which the innermost layer is Ab_2An_3, which in turn becomes more sodic towards the outside. Thus there is a reversal of the normal

order in passing from core to mantle, but the usual order is followed in the successive zones of the mantle. Hibsch explains this by supposing that the cores were formed in an andesitic magma which at a later stage was mixed up with a basaltic magma richer in anorthite; but such an explanation is simply a confession of ignorance as to what happened.

Between felspars and felspathoids the relations are irregular. Sodalite is sometimes enclosed by orthoclase, sometimes interstitial to it, and again the two minerals may form micrographic intergrowths. This is also true of nepheline. Leucite sometimes crystallises at a very early stage, for some of the lavas of Vesuvius contain large crystals of leucite at the time when they are poured out of the volcano. Analcime, in those rocks which contain it, is usually the very last mineral to form, but the "blairmorite" of Canada, which holds over seventy per cent. of analcime, has large crystals of that mineral set in a fine-grained groundmass consisting of smaller analcime crystals, together with pyroxene, nepheline, orthoclase and melanite.

Finally, as regards quartz, the rule is again very often at fault. Apart from the fact that very many rhyolites and pitchstones show crystals of quartz in a glass base, we have evidence even from granites to show crystallisation of quartz before felspar, or at least before the completion of the felspar period. A. Harker and J. E. Marr describe a granite-porphyry at Wasdale, Westmorland, in which the larger felspars enclose perfectly formed quartz crystals, rising to one-fifth of an inch in diameter. In the Rapakiwi granites of Sweden and Finland the quartz typically appears as perfect little bipyramids enclosed in felspar. A. Lagorio, by examining the composition and order of crystallisation of many rhyolites and porphyries, brought out the approximate rule that in rocks of moderate acidity (about 55 to 65 per cent.) the glass base is more acid than the entire rock, while in very acid rocks the base is less acid. In other words, quartz crystallises early from highly siliceous rocks and late from those of moderate acidity. J. H. L. Vogt confirms this, and shows that the boundary lies at about 74 per cent. of total silica.

In short, there is no such thing as a constant order of crystallisation, applicable to all rocks. The order in which the various crystalline phases appear in any particular case is controlled first and foremost by the relative proportions of the components in the magma, and secondly by the relations of isomorphism and solid

solution which exist between them. Other factors which influence the order of crystallisation are the rate of cooling, the concentration of fugitive constituents, the degree of overcooling, and the relative crystallising power of the various phases. Not until a great deal more work has been done in determining the equilibria between rock minerals and their mutual solutions will it be possible to speak with confidence of the order in which crystallisation took place in a given rock.

Compatible and Incompatible Phases. It is a familiar observation to petrographers that leucite, nepheline, olivine and a few other minerals are almost never found in rocks which contain free quartz or tridymite. The implication is that the molecules of these minerals are unstable in the presence of free silicic acid, under such conditions as are realised in magma, because they can combine with it to form higher silicates. Such minerals may be said to be *unsaturated* with silica; while those which are capable of crystallising from magma even in the presence of an excess of silica, may be said to be *saturated* with silica (S. J. S., 1913). Saturated minerals and quartz are therefore compatible phases; unsaturated minerals are incompatible with quartz in an eruptive rock. The common saturated and unsaturated minerals are named below :—

Saturated	*Unsaturated*
All felspars	Leucite
All pyroxenes	Nepheline
All amphiboles	Sodalite, haüyne, nosean
All micas	Cancrinite
Tourmaline	Analcime
Fayalite (iron olivine)	Olivine (except fayalite)
Spessartite	Melanite (andradite)
Almandine	Pyrope
Sphene	Perovskite
Topaz	Melilite
Magnetite	Corundum
Ilmenite	Calcite
Apatite	
Zircon	

The equilibria between leucite and silica, and olivine and silica, were discussed on page 79. In the crucible, olivine (forsterite) and silica can only exist together above 1557°, and leucite and silica only above 1170°. These temperatures are lowered to an

unknown extent by the presence of other constituents in the melt. It was also shown, on page 82, that rapid cooling may cause an unstable association to be preserved. Thus olivine crystals may be preserved in a highly siliceous glass base. Lavas which show this abnormal feature have been described by H. S. Washington at Monte Ferru, Sardinia (page 211) and by H. H. Robinson at San Francisco Mt., Arizona (page 203). A similar effect may be caused by the olivine crystals being enclosed in pyroxene and prevented in this way from reacting with the siliceous residual magma.

That quartz and magnesian olivine are really incompatible in eruptive rocks is shown by a multitude of observations, of which only a few can be mentioned here. The following table shows the relation between silica content and mineralogical development in a series of basalts in the Eureka district of Nevada (A. Hague).

Number	*Silica*	*Olivine*
1.	49.23	Rich in macroscopic secretions
2.	51.86	Rich in microscopic secretions
3.	57.42	Abundant, microscopic
4.	58.06	Easily recognised under microscope
5.	58.26	Only a trace
6.	58.60	None detected
7.	58.64	Detected under the microscope
8.	59.51	None detected
9.	59.64	None detected
10.	60.11	None detected

G. W. Tyrrell has described a series of dolerite intrusions at Kilsyth, Scotland, which contain olivine when quartz is absent, but hypersthene in all cases where quartz is present.

When an olivine-bearing rock is found in contact with siliceous country rocks, reaction takes place between them, leading to the disappearance of the olivine. Sills of olivine dolerite at Nordingra, Sweden, lose their olivine and become quartz-bearing when they come into contact with sandstone or granite (A. G. Högbom). Olivine grains in the Palisade diabase of New Jersey develop mantles of enstatite near the sandstone walls of the intrusion (J. V. Lewis). Many examples of this reaction are furnished by A. Lacroix in his volume on the inclusions of volcanic rocks; quartzose enclosures in olivine-bearing lavas have been partly assimilated by the lava, which in the neighbourhood

of the enclosures loses its olivine and develops pyroxene instead. It is obvious that the rapid freezing of the magma while this process is going on may yield a rock containing both olivine and quartz grains, but the association is none the less an unstable one.

As regards fayalite or iron-olivine the case is different. The pure compound $FeSiO_3$ is not known to be formed in eruptive rocks under any conditions, hence fayalite, Fe_2SiO_4 is the stable form even in presence of free silica. Fayalite has been observed in association with quartz or tridymite in many rhyolites and some granites and syenites. H. S. Washington has described acid lavas from the island of Pantelleria which contains a little fayalite, and he observes that " the olivine found elsewhere in highly siliceous rocks, as granite and syenite, is always fayalite, not common olivine or the magnesian forsterite." Although forsterite and fayalite are isomorphous, it is necessary for the above reason to regard the former as an unsaturated and the latter as a saturated mineral. All common olivine is magnesian and therefore unsaturated.

The same kind of evidence which shows that olivine is incompatible with quartz is available in the case of most of the other minerals which we have placed on the " unsaturated " list. For all of them there is the observed fact of their non-occurrence in quartz-bearing rocks, but in many cases an actual reaction with silica can be demonstrated either in the field or in the crucible. The chemical evidence in the case of leucite has already been given (page 79). Field evidence of the association of quartz and leucite scarcely exists. In some cases where leucite has been said to be present in a quartz-bearing rock, the supposed leucite crystals prove to be little, twinned crystals of cordierite. In other cases, the material is the mysterious substance called " pseudoleucite," and it proves nothing at all about the stability of fresh leucite. The remarkable " leucite-granite-porphyry " which E. Hussak found at Serra de Caldas, Brazil, contains pseudo-crystals of sharp trapezohedral form, composed of orthoclase and nepheline with a little spinel and corundum, set in a fine-grained base of granitic composition. Quartz is never found in the pseudo-crystals, or nepheline in the base, and a narrow mantle of orthoclase laths separates the core of each pseudo-crystal from the siliceous base. Hussak supposed that a granophyric magma had invaded and broken up a leucite-bearing rock; but the question requires further investigation in the field.

Where leucitic lavas meet quartzose rocks, reaction takes place, leading to the disappearance of leucite. A. Lacroix mentions several cases in his book, already referred to. Thus the "leucitite néphélinique" of Korretzberg, Rhenish Prussia, normally contains no felspar, but where it holds quartzose enclosures it develops felspars at the expense of its leucite and nepheline. Similar phenomena are described at Bertrich in the Eifel and at the Kaiserstuhl in Baden.

Evidence of reaction between nepheline-bearing rocks and siliceous rocks with which they are in contact has already been given on page 67, and little more is needed. R. Heinrich describes some basaltic lavas containing both nepheline and olivine, which cut through granite near Rothau in Bohemia. Fragments of the granite which are enclosed in the basalt have been much corroded, and in their neighbourhood nepheline does not appear at all in the basalt, while the olivine grains have been attacked and converted partly or wholly into pyroxene. In other cases it is the quartz grains which are changed. Lacroix records a case in the Vosges Mts. where quartz grains enclosed in nephelinite have been converted into soda-zeolites. F. Cornu observed that fragments of granite enclosed in nepheline basalt at Salesl, Bohemia, have their quartz changed into apophyllite; this observation has been repeated by A. Scheit at Teplitz.

From the experimental side, it may be pointed out that C. and G. Friedel were able to produce either nepheline or albite, leucite or orthoclase, by varying the ratio of silica to alkali in their synthetic experiments. This is confirmed by E. Baur and by C. N. Fenner.

As regards sodalite, haüyne, nosean, analcime and cancrinite, which are closely related to nepheline, there is an initial probability that the behaviour of nepheline will be followed. There is little direct evidence of silicification, but no lack of indirect evidence of the incompatibility of these minerals with quartz. So far as is known, none of them has ever been found in a quartz-bearing rock; their home is among the nepheline syenites and phonolites.

Melilite is confined to lavas of a highly basic nature, in which olivine is nearly always present in abundance, and in which the silica content scarcely rises above 35 per cent. It is also well known as a constituent of very basic furnace slags. Perovskite is commonly associated with melilite and nepheline, but avoids quartzose rocks, in which its place is taken by sphene.

The lime-iron garnet, melanite or andradite, is only known in quartz-free syenites and phonolites, and is probably due in every case to the assimilation of limestone by the magma, that is, it is a product of desilication. The melanite syenite of Assynt, Scotland, occupies an intermediate place between a quartz-syenite and a limestone, and melanite only appears when quartz has disappeared. The magnesian garnet, pyrope, is restricted to very basic rocks such as peridotites, pyroxenites and serpentines, which are generally free from felspar. There is nothing in the known facts of distribution of either melanite or pyrope to suggest that these minerals are capable of forming in presence of an excess of silica.

In the case of corundum, the common association is with plagioclase (Transvaal; Ural Mts.), or nepheline (Canada; India), in quartz-free rocks. The important corundum deposits of the Transvaal are in plagioclase-biotite pegmatites, and A. L. Hall remarks that "not a single example was observed where a corundiferous reef also carried quartz." It is possible, however, that at the very low temperature under which crystallisation takes place in some pegmatites, corundum and quartz may form a stable association, just as calcite and quartz do below 500°. Thus Adams and Barlow remark that in Ontario a "small amount" of quartz has sometimes been found in the corundiferous reefs; and Barlow states that in a pegmatite in Colorado "the corundum seems to favour association with quartz."

As regards spinel there is little evidence, but C. E. Tilley notes that in the garnet-gneisses of South Australia spinel is never found in contact with quartz, but is always separated from it by a shell of garnet or sillimanite.

Calcite has been recognised as a constituent of nepheline-syenites in Ontario, Sweden, and elsewhere, and of quartz-bearing aplites at Gowganda, Canada. The reaction between calcite and silica has already been discussed (p. 52), and in the light of the experimental evidence it would seem to be correct to regard calcite as an unsaturated mineral above 500°, and a saturated one below that temperature, under atmospheric pressure.

REFERENCES.

Adams, F. D. and Barlow, A. E.—Canada, Geol. Survey, Mem. 6, 1910.
Barlow, A. E.—Canada, Geol. Survey, Mem. 57, 1915.
Baur, E.—Zeitschr. phys. Chem., 1902, 567.

Bayley, W. S.—U.S. Geol. Survey, Bull. 109, 1893, *47*.
Berwerth, F. M.—Jahrb. Siebenbürg. Karpathenvereins, 1905, *12*.
Bowen, N. L.—(diopside-anorthite) Amer. Jour. Sci., 1915, *161*.
do. —(plagioclase felspars) Amer. Jour. Sci., 1913, *577*.
do. (order of crystalln.) Jour. Geol., 1912, *455*.
do. and Andersen, O.—Amer. Jour. Sci., 1914, *487*.
Brögger, W. C.—Zeitschr. Kryst. 1890, *218*.
Chrustchoff, K. von—Tschermak's Min. Pet. Mitth., 1888, *470*.
Cornu, F.—Centralblatt Min., 1907, *242*.
Drysdale, C. W.—Canada, Geol. Survey, Mem. 56, 1915, *110*.
Evans, J. W.—Quart. Jour. Geol. Soc., 1925, cx.
Fenner, C. N.—Amer. Jour. Sci., 1913, *357*.
Fermor, L. L.—Records Geol. Survey, India, 1913, *41*.
Fouque, F. and Michel Levy—Synthèse des Mineraux et des Roches, Paris, 1882, *155*.
Foye, W.—Jour. Geol., 1918, *529*.
Friedel, C. and G.—Bull. soc. min. France, 1890, *129*; 1896, *5*.
Green, J. F. N.—Proc. Geol. Association, 1919, *153*.
Geijer, P.—Geology of Kiruna District, Stockholm, 1910, *7*.
Hackmann, V.—Bull. Comm. Geol. Finlande, no. 11, 1900.
Hague, A.—U.S. Geol. Survey, 3 Ann. Rep., 1883, *241*.
Hall, A. L.—S. Africa, Geol. Survey, Mem. 15, 1920.
Harker, A.—Scotland, Mem. Geol. Survey (Small Isles), 1908.
do. and Marr, J. E.—Quart. Jour. Geol. Soc., 1891, *288*.
Hatch, F. H.—Quart. Jour. Geol. Soc., 1889, *342*.
Heinrich, R.—Neues Jahrbuch Min., B.B.23, 1907.
Hibsch, J. E.—Tschermak's Min. Pet. Mitth., 1897.
Högbom, A. G.—Geol. Föreningens Förhandl., 1909, *347*.
Horne, J. and Teall, J. J. H.—Trans. Roy. Soc. Edinburgh, 1892, *163*.
Hussak, E.—Neues Jahrbuch Min., 1900, *22*.
Iddings, J. P.—Bull. Phil. Soc., Washington, 1889, *85*.
Johnston, J.—Jour. Franklin Inst., 1917, *1*.
do. and Adams, L. H.—Amer. Jour. Sci., 1911, *501*.
Lacroix, A.—Les Enclaves des Roches Volcaniques, 1893.
do. —Nouvelles Archives du Museum, 1902, *11*.
Lagorio, A.—Tschermak's Min. Pet. Mitth., 1887, *421*.
Lewis, J. V.—New Jersey, Ann. Rep. State Geologist, 1907.
Machado, J.—Tschermak's Min. Pet. Mitth., 1888, *318*.
Merrill, G. P.—Amer. Jour. Sci., 1888, *488*.
Miers, H. A.—Ann. Rep. British Assn., 1905.
Morey, G. W. and Bowen, N. L.—Amer. Jour. Sci., 1922, *1*.
Morozewicz, J.—Tschermak's Min. Pet. Mitth., 1898.
do. — do. 1902, *238*.
Ramsay, W. and Berghell, H.—Geol. Fören. Förhandl., 1891, *300*.
Rankin, G. A.—Amer. Jour. Sci., 1915, *1*.
Robinson, H. H.—U.S. Geol. Survey, Prof. Paper 76, 1913.
Scheit, A.—Tschermak's Min. Pet. Mitth., 1915, *227*.
Shand, S. J.—Trans. Edinburgh Geol. Soc., 1910, *376*.
do. —Trans. Geol. Soc. S. Africa, 1921, *111*.
do. —(Silica-saturation) Geol. Mag., 1913, *508*.
Shannon, E. V.—Jour. Geol., 1919, *579*.
Streng, A.—Neues Jahrbuch Min., 1888, *221*.
do. —Verein für Erdkunde zu Darmstadt, 1890, *28*.
Tammann, G.—Kristallisieren und Schmelzen, 1903.
Tilley, C. E.—Geol. Mag., 1921, *310*.

Tyrrell, G. W.—Geol. Mag., 1909, *299*
Vogt, J. H. L.—(Freezing point) Jour. Geol., 1922, *611*.
do. —(Ternary eutectic) Jour. Geol., 1921, *337*.
do. — do. Videns. Selsk. Skrifter, no 10, 1908.
do. —(Melilite-magnetite) Vid. Selsk. Skrifter, no. 8, 1903, *115*.
Wagner, P. A.—The Diamond Fields of Southern Africa, 1914.
Walker, F.—Trans. Roy. Soc. Edinburgh, 1923, *372*.
Washington, H. S.—(Monte Ferru) Amer. Jour. Sci., 1915, *513*.
do. —(Pantelleria) Jour. Geol., 1914, *653*.
Williams, G. H.—American Geologist, 1890.

CHAPTER VI.

THE CLASSIFICATION OF ERUPTIVE ROCKS.

A GREAT deal of confusion and misunderstanding surrounds the subject of the classification of eruptive rocks, and this is due, not only to the complexity of the problem, but also to the circumstance that the aims, methods, and limitations of the science of classification itself have not always been properly appreciated by petrographers. The student of rocks will learn far more about scientific classification from purely philosophical writers, such as John Stuart Mill and William James, than from any source in petrographical literature; hence it will be advisable to open the discussion of the classification of rocks with some paragraphs on classification in general.

Classification begins when people give names to things. When certain rocks, such as basalt, porphyry, and granite were given these distinctive names to mark certain differences in their appearance, the classification of rocks was set afoot. This kind of classification is what Mill calls "a mere incidental effort consequent on the use of names," and because popular names are generally given to things in a very loose way, without careful discrimination, so the resulting classification is a very imperfect thing. We shall find it convenient to refer to it as a *classification of the first kind.*

At a later day, when the objects attract the critical attention of science, another kind of classification becomes necessary, in which the most suitable grouping of the objects is the first consideration, and the naming of them is a secondary matter which is governed by the grouping. This we may call a *classification of the second kind.* Of this kind of classification, Mill says

"Classification, thus regarded, is a contrivance for the best possible ordering of the ideas of objects in our mind; for causing the ideas to accompany or succeed one another in such a way as shall give us the greatest command over our knowledge already acquired, and lead most directly to the acquisition of more."

"The general problem of classification, in reference to these purposes, may be stated as follows: To provide that things shall be thought of in such groups, and those groups in such an order, as will best conduce to the remembrance and to the ascertainment of their laws."

" The ends of scientific classification are best answered when the objects are formed into groups respecting which a greater number of general propositions can be made, and those propositions more important, than could be made respecting any other groups into which the same things could be distributed."

Now petrography has a highly developed classification of the first kind, for more than four hundred and fifty different names have been given to eruptive rocks to mark minute points of difference between them. But of the way in which this classification has grown up, it has been said with entire justice that " the method of petrographers in proposing names, so far as any method is discoverable, is to give an independent name to each rock which is slightly different from any previous rock found, without reference to any definite plan of nomenclature " (C. R. van Hise).

In attempting to set up a classification of the second kind, to take the place of the disorderly collection of names that does duty as a classification now, what is required of us is that we should pay less attention than we have done in the past to the individual peculiarities of rocks, and more to the laws that govern their formation. The laws are those of physics and chemistry. The problem before us, then, is to elicit the *physico-chemical significance* of the various geographical, geological, textural and mineralogical characters that eruptive rocks present, and to express this in a classification.

As our knowledge of the physical chemistry of rocks is still far from perfect, it is clear that a classification set up at the present day cannot make any claim to finality. We must make it as perfect as we can, in the light of our present knowledge, and be prepared to modify it as knowledge increases. If we start off with a proper conception of the purpose which our classification is to serve, and if we base it on the facts of chemical petrology as we know them now, it will not be difficult to modify and adjust the classification so as to bring it into harmony with other facts yet to be discovered.

To understand any chemical system completely, it is necessary to know

(1) The chemical components, and the concentration of each;
(2) The phases developed in the system during crystallisation;
(3) The changes of temperature and pressure to which the system has been subjected.

In a chemical system that has been fully studied, if we are told the concentration and the physical conditions, we can predict the phases that will be formed. Conversely, if we know the concentration and the phases present, we can deduce the physical conditions. The last is the problem with which we are faced in the study of eruptive rocks. The components of the system are discovered by chemical analysis of the rock; the phases are the minerals which we identify by the aid of the miscroscope; from these data, together with such information as we can extract from the structure and environment of the rock mass, we have to deduce the chemical and physical conditions under which the freezing of the magma took place.

In doing this, we require the aid of a mental instrument to express and record and correlate our observations. This instrument, beginning as a mere aid to memory, will develop as our knowledge grows into a physico-chemical classification of rocks.

We shall now consider, in turn, the value of the chemical composition, the texture, the geological habit, the geographical distribution, and the mineralogical composition of a rock mass as aids to the understanding of the magma system out of which it developed.

The chemical composition of the rock as an aid to the understanding of the magma-system. We have already (in Chapter II.) discussed the components of the magma-system, in so far as these can be determined by quantitative chemical analysis of eruptive rocks. It was shown that some twenty acidic and basic oxides enter in appreciable quantities into the composition of eruptive rocks, and that about half of these oxides are almost always present in quantities greater than one per cent. Each oxide has a range from nothing to a maximum which is in some cases more than half the mass of the rock.

An important question arises at once: how far does the composition of the rock correspond to that of the magma from which it was formed? There are certain considerations which make it probable that no rock ever has exactly the same composition as its magma, and that in some cases the discrepancy may be a large one.

The fugitive constituents of the magma were discussed in Chapter III., and it was shown that all magma probably carries some volatile and water-soluble compounds which are lost during the process of freezing. Though there is no reason to suppose

that the mass of the fugitive constituents is ever very great, yet their influence in reducing viscosity and promoting crystallisation and chemical reaction gives them an importance which is out of all proportion to their actual mass. Of these constituents, in general, the analysis of a rock tells us little or nothing.

Again, it is inevitable that during the long-continued crystallisation of a large body of magma there should be a certain amount of separation of the products of crystallisation, in virtue of their different densities. That heavy crystals tend to sink and light ones to float can be demonstrated even in the crucible, and there is little doubt that this process is operative to some extent in natural reservoirs of magma. But a rock that is formed wholly or in part by the accumulation of heavy crystals at the bottom of a body of magma, or the rising of light crystals or a light liquid residuum to the higher levels of the reservoir, must have a composition very different from that of the magma which gave rise to it. We may illustrate this by reference to the Moyie sill, British Columbia, which has been described by R. A. Daly and S. J. Schofield. There is a remarkable difference in composition between the body of this sill and its upper layer, as the following analyses show.

	Main Mass of sill	*Upper portion of sill*
SiO_2	51.92	72.42
TiO_2	0.83	0.68
Al_2O_3	14.13	10.47
Fe_2O_3	2.08	0.83
FeO	8.11	5.50
MnO	0.35	0.16
MgO	6.99	0.41
CaO	10.92	2.53
Na_2O	1.40	1.93
K_2O	0.49	2.94
H_2O-	0.12	0.06
H_2O+	1.56	1.11
P_2O_5	0.08	0.11
CO_2	—	0.61
	99.78	99.76

The upper portion of the sill is granite, while the main mass is gabbro; but both were formed from the same magma.

The discrepancy between rock and magma is most strikingly illustrated when there has taken place, in one body of magma, both a sinking of early formed crystals and a rising of residual liquor. Such a case is perhaps presented by the Insizwa intrusion of Griqualand West, South Africa, which was described by A. L. Du Toit. The lower portion of this intrusion is rich in olivine, but the upper portion is largely felspathic and carries interstitial quartz. It would be quite impossible to deduce the composition of the initial magma from the study of either of these rock-facies by itself. In short, when a crystallising body of magma becomes differentiated under the influence of gravity, rocks are sometimes formed which are mere fortuitous aggregations of solid phases in proportions which bear little relation to the composition of the original magma.

It is not intended, by these remarks, to minimise the importance of making numerous and accurate rock analyses, but only to show that the chemical analysis of a rock, however accurately it is performed, must often fail to give a true idea of the composition of the magma from which that rock crystallised. But for the understanding of the chemistry of the system, it is the composition of the magma, not that of the rock, that is all-important. In the absence of any other means of attacking the problem, however, we are compelled to accept the data furnished by chemical analysis of a rock as the best available approximation to the composition of the magma from which it was formed.

Many thousands of eruptive rocks have been analysed, and we may enquire whether any relation can be established between the chemical composition and the other characters of a rock. For example, if we are given a chemical analysis of a certain rock, can we deduce from it the mineralogical composition of the rock, or any of its geological characters?

Taking the second point first, we can answer it by comparing the composition of rocks of different geological habit; for example, plutonic rocks and lavas. Suitable data for the comparison are afforded by R. A. Daly's computation of the average composition of different rock "types." Column I., below, gives Daly's statement of the average composition of 236 granites; column II. is a combined average for 114 rhyolites and quartz-porphyries.

	I.	II.
SiO_2	70.47	73.47
TiO_2	.39	.31
Al_2O_3	14.90	14.20
Fe_2O_3	1.63	1.50
FeO	1.68	.92
MnO	.13	.11
MgO	.98	.46
CaO	2.17	1.36
Na_2O	3.31	3.25
K_2O	4.10	4.32
P_2O_5	.24	.07
	100.00	99.97

The comparison of these figures brings out a conclusion to which Rosenbusch first drew attention; namely, that lavas are in general slightly richer in silica and alkalies, and poorer in iron, lime and magnesia, than plutonic rocks of similar mineralogical composition. But the general similarity of the figures for granite and for rhyolite is such as to show that no precise correlation can be effected between the chemical composition of the rock and its geological habit. Washington's tables of chemical analyses of rocks, arranged according to the norm system devised by Cross, Iddings, Pirsson and Washington, point to the same conclusion, for every sub-range of the system holds dyke-rocks and lavas as well as plutonic rocks. There is therefore no definite relation between the chemical composition of any rock and its geological habit, or, we may add, its structure and texture, since the latter are largely controlled by geological conditions.

As for the mineralogical composition of a rock, this is of course dependent in the first instance on its chemical composition, but is the dependence such that the former can be directly deduced from the latter? Only to a limited extent, for rocks of very simple composition. For example, since no known rock-forming silicate holds more than 69 per cent. of silica, it is clear that a fresh rock which is more siliceous than that, must of necessity contain free silica in the form of quartz or tridymite. In the same way, since no rock-forming silicate has more than 55 per cent. of alumina, any rock which exceeds that proportion must carry aluminium in the form of the oxide (corundum) or the aluminate (spinel). But a rock may hold much less than 69 per cent. of

total silica and yet contain free quartz, or much less than 55 per cent. of total alumina, and still hold corundum; so *except in extreme cases* no deduction can be made from the analytical data as to the presence or absence of quartz or corundum respectively.

Potash and soda, in felspars and felspathoids, are bound up, molecule for molecule, with alumina; consequently, if the molecular proportion of alumina in a rock analysis is less than that of soda and potash together, it follows that the excess of alkalies must be present in the form of a non-aluminous compound such as ægirine, riebeckite, eudialyte, or some other uncommon mineral.

If, on the other hand, the molecular proportion of alumina exceeds the total of the soda, potash, lime and magnesia molecules, this must indicate the presence of one or other of the micas, or of corundum, or topaz.

Lime is a constituent of so many rock-forming minerals, both with and without alumina and with and without silica, that it is hardly ever possible to deduce from the analytical data the precise combinations into which lime enters, and their relative proportions. The same thing is true of magnesia, which is an important constituent of micas, pyroxenes, amphiboles, olivine, tourmaline, garnet and spinel; and of the iron oxides, which, besides entering into all the above combinations, can also appear in the free state as hematite or magnetite. The sheer impossibility of distributing the available alumina and silica molecules correctly between alkalies, lime, magnesia, and iron oxides is brought out clearly by the following equations, in which the phases on the left-hand side have exactly the same ultimate composition as the phases on the right-hand side, in each case.

$$\underset{\text{(anorthite)}}{CaAl_2Si_2O_8} + \underset{\text{(olivine)}}{Mg_2SiO_4} = \underset{\text{(diopside)}}{CaMgSi_2O_6} + \underset{\text{(spinel)}}{MgAl_2O_4} + \underset{\text{(quartz)}}{SiO_2}$$

$$\underset{\text{(anorthite)}}{3\,CaAl_2Si_2O_8} = \underset{\text{(garnet)}}{Ca_3Al_2Si_3O_{12}} + \underset{\text{(corundum)}}{2Al_2O_3} + \underset{\text{(quartz)}}{3\,SiO_2}$$

$$\underset{\text{(leucite)}}{KAlSi_2O_6} + 2\underset{\text{(enstatite)}}{MgSiO_3} = \underset{\text{(orthoclase)}}{KAlSi_3O_8} + \underset{\text{(olivine)}}{Mg_2SiO_4}$$

$$\underset{\text{(anorthite)}}{CaAl_2Si_2O_8} + \underset{\text{(olivine)}}{Mg_2SiO_4} = [\underset{\text{(augite)}}{MgSiO_3 + CaSiO_3 + MgAl_2SiO_6}] = \underset{\text{(garnet)}}{CaMg_2Al_2Si_3O_{12}}$$

$$\underset{\text{(muscovite)}}{H_2KAl_3Si_3O_{12}} + \underset{\text{(diopside)}}{CaMgSi_2O_6} + \underset{\text{(quartz)}}{SiO_2}$$
$$= \underset{\text{(orthoclase)}}{KAlSi_3O_8} + \underset{\text{(enstatite)}}{MgSiO_3} + \underset{\text{(anorthite)}}{CaAl_2Si_2O_8} + H_2O$$

When many analyses are compared, there often seems to be a roughly concomitant variation of calcium with magnesium, due to the fact that these elements maintain a nearly constant relation

in pyroxenes and amphiboles. But clearly no rule can be founded on this, for an anorthite rock, rich in calcium, may hold no magnesium in any form, while an olivine rock, rich in magnesium, may be entirely free from calcium.

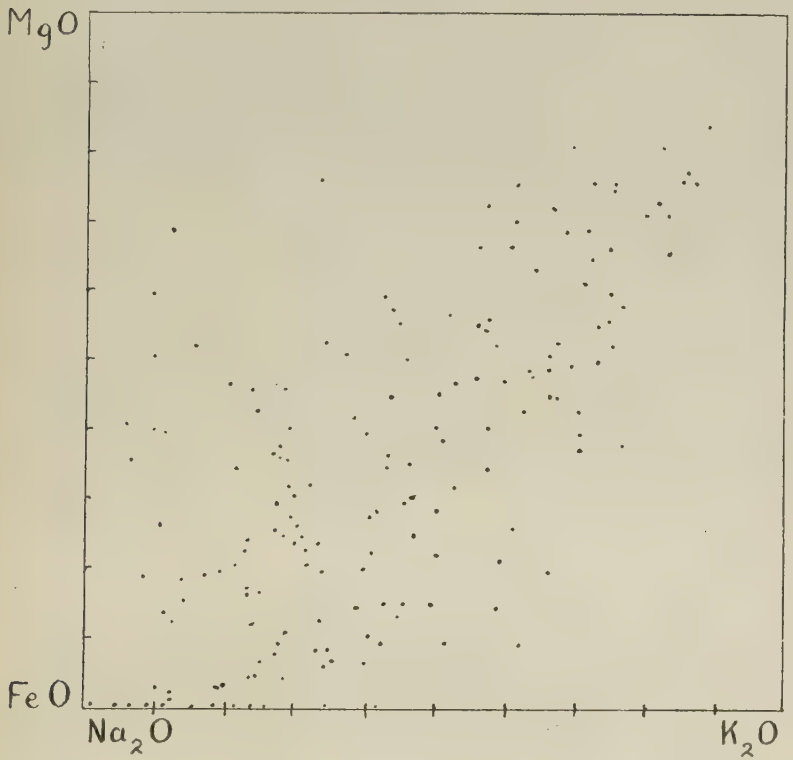

FIG. 19. A plotting of nearly two hundred rock analyses, to show that potash and magnesia on the one hand, and soda and iron oxide on the other, tend to vary together. (H. S. Washington.)

H. S. Washington directs attention to a sympathetic relation that obtains between magnesium and potassium, on the one hand, and iron and sodium on the other. It is a familiar observation that the sodium iron pyroxenes and amphiboles (ægirine, riebeckite, arfvedsonite, etc.) are typical of soda-rich rocks in which potassium and magnesium play a subordinate part. On the other hand, many rocks in which potash is predominant over soda show also magnesia in excess as compared with iron oxides.

The only minerals that hold both high potash and high iron are some of the less common varieties of the dark micas, but all the common micas hold more magnesia than iron. The correctness of the correlation asserted by Washington is clearly shown by a diagram (*Fig.* 19) in which some 200 selected analyses have been plotted with the ratio of $Na_2O : K_2O$ as abscissa and that of $FeO : MgO$ as ordinate. The clustering of the points in a band running across the field from the soda-iron corner to the potash-magnesia corner is unmistakeable.

Such facts as these are of great interest and importance for the theory of petrogenesis, and it is the task of petrology to face them, and, in time, to explain them; but they cannot be said to possess any obvious value for the purpose of classification. If high potash necessarily involved high magnesia, and if high soda were always accompanied by a high iron content, these rules would give us an admirable basis for classification; but as there are rocks rich in potash yet almost without magnesia, and rocks rich in soda but free from iron, it is clear that the facts express only a tendency, not a law, and this tendency is not definite enough for use in the framework of a classification.

The same thing may be said of a number of other generalisations relating to the conjunction of certain elements in eruptive rocks; such as the association of barium with potassium; of cerium and zirconium with sodium; of nickel and chromium with magnesium; of titanium with iron and sodium. All of these are tendencies rather than regularities, and they are not constant enough to have any value as factors in classification.

The plain conclusion that is to be drawn from the above considerations is that, although the ultimate chemical composition is one of the essential characters of a rock-magma, and although it is quite feasible and perfectly legitimate to classify rocks on the basis of their ultimate chemical composition, yet *for the purposes of general petrology* such a classification must be unsatisfactory for it fails entirely to express any of the mineralogical or geological characters of rocks or any of the conditions that govern the freezing of rock-magmas. No general propositions can be asserted of the groups in such a classification, consequently the aim of a scientific classification is not attained.

The classification of rocks by their chemical composition alone has been carried to a high degree of completeness in the quantitative system devised by Cross, Iddings, Pirsson, and Washington. Since this system was first introduced in 1903, there has been

much heated discussion of its merits and its utility. It is not proposed here to enter into that discussion at all. From what has already been said, it will be apparent that a classification which takes into account only one property or aspect of a set of objects can only be thoroughly satisfactory from that one aspect. When the ultimate chemical composition of a rock is the only aspect of it which it is desired to discuss, then the Quantitative Classification serves its purpose most usefully. But to discuss rocks in terms of ultimate chemical composition, without reference to their actual mineralogical development, is to discuss a chemical system in terms of its components and ignore the phases, and brings us no nearer to a philosophical treatment of the subject.

It has been said that " it would be absurd that we should not be able to determine the genus and species of an animal without first killing it." Similarly we may say that it would be absurd, from a general petrographic point of view, that we should not be able to name a rock until we had determined the precise amount of every element contained in it.

In some rock classifications in current use, the mere percentage of silica in a rock is made the prime factor in its classification. All rocks having more than a certain arbitrarily fixed proportion of silica are described as " acid rocks," and those with smaller quantities of the same constituent are " intermediate," " basic " or " ultra-basic " as the case may be. But what general propositions can be made regarding such groups? A so-called acid rock (which, according to the system of F. H. Hatch, is one containing more than 66 per cent. of silica), may contain quartz or it may not; it will probably hold much alkali-felspar, but in some cases it will have little felspar and in an extreme case none at all; as regards other minerals which may or may not be present in the rock, no statement whatever can be made. A basic rock (that is, according to Hatch, one with less than 52 per cent. of SiO_2) may in spite of its name hold free quartz, and it is impossible to say anything whatever about other constituents, as regards either their presence, their absence, or their proportions. In short, the silica percentage, in addition to being very difficult to determine, gives in general no indication whatever of any other property of the rock.

[The determination of the percentage of silica in a rock requires an elaborate procedure of sampling and crushing the rock, followed by a tedious and difficult fusion in a platinum crucible; thereafter solution and filtration of the melt, evaporation of the filtrate to dryness at least twice, followed each time by filtration; then ignition and weighing of

the residue, followed by treatment of the residue with sulphuric and hydrofluoric acids, and another ignition and weighing. It is quite certain that many who profess to use the silica percentage method of classifying rocks never take the trouble to make an actual determination of silica at all, but content themselves with guessing the silica percentage from the mineralogical composition of the rock!]

The texture of rocks as an aid to the understanding of the magma-system. A prominent place was always assigned to texture in the older classifications of rocks, and with good reason. Texture is a prominent character, and it can be correlated to a certain extent with other matters such as geological occurrence and the conditions that prevailed during the cooling of the magma. Whitman Cross has shown that the conception of texture involves three distinct factors, which he defines as

(1) Crystallinity, or the degree of crystallisation;

(2) Granularity, or the magnitude of the crystals;

(3) Fabric, or the shape and arrangement of the crystals.

As regards crystallinity and granularity, it is well known that some rocks are wholly glassy, while many rocks consist partly of crystals and partly of glass. The crystalline rocks differ among themselves as regards the magnitude of their crystals, some being composed of crystals from an inch to a foot in diameter, while others, which are just as completely crystallised, have individual crystals so small as to require a microscope for their recognition. In other cases still, the ground mass of a rock appears to be structureless, yet its behaviour towards polarised light shows that it actually consists—in part at least—of sub-microscopic crystals.

Again, the crystals of one mineral are often much larger than those of another mineral in the same rock, the most abundant mineral usually forming the largest crystals. Thus in a typical granite the majority of the felspar crystals may be measurable in centimetres, the quartz and mica crystals in millimetres, and the apatite and zircon only in tenths or hundredths of a millimetre. Inequality of grain is still more strikingly shown by some dyke-rocks and lavas in which a single mineral gives rise to two series of crystals, an older series of large crystals and a younger series of small crystals which have perhaps no more than a tenth or a twentieth of the diameter of the former ones. This is the well-known "porphyritic texture." Every porphyry is made up of two sharply contrasted elements—the large crystals, which we shall call *insets*,* and the fine-grained groundmass or base.

* The writer prefers this simple English word, which has very nearly the same meaning as the German *Einsprengling*, to the bastard Greek fabrication "phenocryst."

An exaggerated importance has sometimes been assigned to the porphyritic texture, for it has been supposed that the insets in porphyritic rocks were formed when the magma was deep down in the crust, at higher temperature and pressure than those that obtained when the groundmass crystallised. It is certainly true that lava flowing from the crater of a volcano sometimes contains ready-formed crystals, such as the large leucite crystals in some of the lavas of Vesuvius. There is no need, however, to suppose that the insets were formed under very different conditions from the smaller crystals which grow later, because the rate of growth of some minerals (including leucite) is rapid, and the early formed crystals, being few in number, are most favourably situated for attaining a large size. L. V. Pirsson has brought forward some strong field evidence against the idea of the deep-seated origin of insets, and N. L. Bowen has shown experimentally that perfectly continuous crystallisation may give the appearance of crystallisation in two generations. The first-formed crystals grow rapidly, until a period is reached when the increasing viscosity of the magma, or the degree of undercooling, causes new centres of crystallisation to appear in large numbers. When the whole mass has frozen, there will be a few large insets and a multitude of small groundmass crystals, although crystallisation has been continuous and the pressure has not changed.

Both field and laboratory evidence demonstrate that high crystallinity and high granularity are favoured by slow cooling and by the presence of volatile fluxes, while deficient crystallinity and a low degree of granularity may be due either to rapid cooling or to the loss of fluxes, or to both causes combined. Rocks of coarsest grain are accordingly found in large intrusive masses, but also in smaller masses where fluxes are abundant, such as pegmatite veins. Fine grain is characteristic of small intrusions and marginal facies, and of lava flows, from which the loss of heat and of fluxes have been comparatively rapid. The glassy and partly glassy rocks are found only in lava flows, narrow dykes, and the selvages of dykes, where cooling and loss of fluxes occurred too rapidly for crystallisation to set in.

Here we have generalisations of some importance, based on a set of obvious characters, and justifying the separation of the *deep-seated* or *plutonic* rocks (which crystallised deep down in the crust, and have only reached the surface in consequence of prolonged erosion of overlying strata) from the *lavas* or *volcanic rocks* which were poured out on the surface. H. Rosenbusch

went further than this, and set up a third group of " dyke-rocks " (*Ganggesteine*) characterised by textures intermediate between those of the former groups. But since every known variety of texture, from the most coarsely crystalline to the completely glassy, is to be found among rocks that occur in the form of dykes, it is clear that this procedure can not be followed without abandoning the correlation between texture and mode of occurrence which distinguishes the plutonic and volcanic groups. So long as we maintain, as Ferdinand Zirkel did, *two* textural groups only, then we can establish definite and important propositions concerning them; but for *purely petrographical* (as distinct from geological) *purposes* there is no justification for the erection of a separate group of dyke-rocks which share the characteristics of the former groups but have no features peculiarly their own.

With regard, then, to crystallinity and granularity, we distinguish two great groups of rocks, the first of which includes all deep-seated rocks and the more coarse-grained dyke-rocks, while the second includes all microcrystalline, cryptocrystalline, and glassy rocks whether they occur in dykes or in lava-flows. The rocks of the first group are well-crystallised or *eucrystalline;* those of the second group are relatively or actually ill-crystallised or *dyscrystalline.* The following propositions may be stated regarding the physico-chemical conditions that prevailed in each case.

(a) *Eucrystalline rocks.* The rate of cooling was slow, hence the crystallisation period was prolonged. Loss of fluxes was also slow, so that the magma, as crystallisation advanced, tended to be progressively enriched with fugitive constituents; consequently crystallisation was complete, and the last portions of the magma to freeze sometimes formed the largest crystals (in pegmatite veins and drusy cavities). Minerals containing hydrogen or hydroxyl, such as the micas and tourmaline, are common, and crystals of late formation are crowded with minute bubbles of water and gas. The majority of these rocks hold quartz, which is always the last or one of the latest minerals to crystallise; tridymite is not found, and leucite and melilite are excessively rare. The pressure prevailing during cooling was generally high, but the temperatures of beginning and ending crystallisation were generally lower than in the next group.

(b) *Dyscrystalline rocks.* The loss of heat from the magma to the atmosphere or to surrounding rocks was rapid, and it was accompanied by a rapid loss of fugitive constituents. The

crystallisation period was therefore short, and the residual magma tended to be progressively impoverished as regards fluxes; consequently crystallisation often failed to be completed, and the last portion of magma then solidified as glass. Hydrous minerals such as mica and tourmaline are relatively scarce; so are liquid and gas bubbles, and the inclusions within crystals are mostly composed of glass or stony matter. Quartz is less common than in the preceding group, and it has often crystallised at an early stage; tridymite sometimes accompanies or replaces it. Leucite is comparatively frequent; olivine is also commoner than in eucrystalline rocks and so is melilite; in general the condition of undersaturation with silica is commoner in this group than in the former one. The pressure prevailing during crystallisation was low, but the temperature was high—occasionally high enough to melt sedimentary rocks in the contact zone—and it is probable that crystallisation began at a considerably higher temperature than in the former group.

Under the heading of *fabric* we include such matters as the shape and arrangement of the various constituents, and the intergrowths of minerals with one another. It is evident that crystals formed at an early stage in the freezing of the magma have a better chance of developing their characteristic shapes than those formed at a later period, for the former are able to grow without hindrance in all directions, while the latter are hampered by their environment. The best-shaped crystals in a rock are consequently those of early formation, so to a certain extent the *degree of idiomorphism* shown by the crystals of any mineral may be taken as an indication of the early or late crystallisation of that mineral. But the value of this generalisation may be destroyed in consequence of reaction taking place between the early-formed crystals and the residual magma. Thus olivine often crystallises at an early stage, and subsequently undergoes partial resorption with formation of pyroxene; such relics of the olivine crystals as survive are then rounded or irregular in shape. Quartz crystallises in perfect hexagonal bipyramids from many lavas, but at a later stage the crystals begin to redissolve, and their characteristic shape is gradually lost. And when the freezing of a magma is accompanied by contraction and production of shrinkage-cavities, such as are exhibited by many granites and rhyolites, then these cavities may be lined with beautifully idiomorphic crystals which are of later formation than those that constitute the bulk of the

rock. Thus great care is necessary in the interpretation of the degree of idiomorphism shown by the various minerals in an eruptive rock.

When two minerals, which are not isomorphous, crystallise at the same time, they may either form separate crystals or the two kinds of crystals may be intergrown, as in graphic granite. Such structures as the graphic and the ophitic have often been supposed to indicate the crystallisation of the components in the form of a binary eutectic. This idea has remained popular in spite of the observation that artificially prepared eutectics of metals, salts and simple silicates seldom show any structures which might be regarded as characteristic of the eutectic condition. The existence of a constant ratio between quartz and orthoclase, or quartz orthoclase, and albite, in graphic granite has been questioned, and there can be no eutectic relation between two minerals such as plagioclase and augite, each of which is itself a solid solution whose composition varies continuously as the system cools down. Yet E. V. Shannon has described graphic intergrowths of plagioclase and augite in a diabase in Massachusetts. For these reasons it would be very unsafe to conclude that because two minerals are intergrown, they must have crystallised eutectically. If that thesis could be established, then this aspect of texture would at once become a character of much importance as indicating the history of crystallisation in the magma; but if such intergrowths as we have discussed are not eutectic mixtures, then their importance in classification is small.

Some of the curious varieties of fabric shown by fine-grained dyke rocks and lavas seem to have been produced by the devitrification of an originally glassy groundmass. All the stages in the conversion of a pure glass into a cryptocrystalline stony material, such as one can study in badly prepared glassware, are reproduced in natural lavas. The most characteristic stage in the process is the appearance of *spherulites*, or spherical bodies built up of radiating crystalline fibres. In artificial soda-lime glass the spherulites are composed of a calcium silicate; but in the highly siliceous and aluminous rock glasses they consist of interlocking fibres of quartz and felspar.

The question of the order of crystallisation of the minerals in eruptive rocks was discussed in Chapter V. It is only through the study of texture (crystallinity, granularity, and fabric) that we can gain any information about the actual sequence of crystallisation, and this consideration would seem to confirm the view that

the texture of rocks should play an important part in their classification. The matter has already been discussed, and we have seen how difficult it is to interpret the observations correctly; indeed theory and observation often seem to contradict each other flatly. There is no field of petrological inquiry which stands in greater need of investigation than the order of crystallisation of the minerals in rocks. If magmas behaved as simply as certain solutions of metals and salts, it would be possible to classify them in accordance with the sequence of events during crystallisation; but all our observations show that the history of a natural rock-magma is much more complex than that of any simple system such as a metallic alloy. The complexity is introduced partly by the presence of unknown fugitive constituents in the magma, and also by the fact that most of the common rock-minerals are not simple compounds but solid solutions.

In the meantime, and probably for many years to come, the order of crystallisation will not be able to take the place to which its importance would undoubtedly entitle it in the classification of rocks.

It follows, then, that *in the present state of knowledge* it would not be justifiable to attach much weight to fabric in a classification of rocks; it must take quite a subordinate place, from which, however, it may yet be elevated if further discovery should attach a fuller meaning to it.

It should be noted, finally, that no aspect of texture can be fully described without reference to specific minerals; thus a classification can not be based on texture without being based at the same time on mineralogical constitution.

Geological habit and geographical distribution as aids to the understanding of the magma-system. The geological habit of an eruptive rock mass is the character that appeals most to a field geologist, and it is natural that he should desire to have a classification based in part at least upon this feature. But the nature of a rock, considered as a mineral aggregate, and the form of a rock mass, considered as a geological unit, are such widely different matters that one must ask whether any useful purpose is to be served by combining them in the framework of a classification. In how far can the geological habit of a rock be correlated with any of its other characters? If one considers only the wide groups of plutonic rocks, dyke rocks and lavas, then there is of course a rough relation between habit and texture, of

which we have already spoken. But even this is by no means constant, for there are dyke rocks with all the textures of plutonics, and plutonic rocks with the textures of minor intrusions. The controversies which have arisen from time to time, as to whether a certain eruptive sheet incorporated with sediments was a sill or a contemporaneous lava-flow, have shown repeatedly that texture affords no reliable criterion by which to distinguish between these two modes of occurrence.

It follows then that the study of rocks as mineral aggregates can gain nothing by being complicated by geological issues. It is equally evident that the study of rocks as geological masses cannot be helped on by the introduction of irrelevant mineralogical details. In short, this is emphatically a case where two independent classifications are better than one.

It is sometimes contended that eruptive rocks fall into two strongly contrasted groups, the *alkaline* and the *alkali-calcic*, which are characteristically developed in the Atlantic basin and the Pacific region respectively. More precisely, the alkaline rocks are supposed to be developed especially in connection with block- and trough-faulting in the more stable regions of the earth-crust, and the alkali-calcic rocks to be developed particularly in the unstable, folded belts.

The characters of the alkaline or Atlantic suite of rocks are summarised as follows by Harker: Alkali-felspars are present in all but those of low acidity; microperthitic and cryptoperthitic intergrowths are common. Felspathoids are often developed in addition to the alkali felspars; micas and garnets are of common occurrence; and so are soda-bearing pyroxenes and amphiboles. Quartz is confined to the most acid types.

The characters of the alkalicalcic or Pacific suite are said to be: relatively great abundance of soda-lime felspars, and scarcity of the alkaline variety. The soda-lime felspars often exhibit zonary banding. Felspathoids are not found, micas only appear in the more acid types, and the pyroxenes and amphiboles belong to the common, soda-free varieties. Quartz is present in many of these rocks, even when the total silica is low.

F. Becke adds the observation that, in alkalicalcic rocks, the composition of the plagioclase corresponds closely to that of the rock, those rocks that have the greatest proportion of dark minerals having the most calcic plagioclase. In alkaline rocks, on the other hand, the composition of the plagioclase bears no such simple relation to that of the rock, alkali felspars being found

even in melanocratic rocks and fairly calcic felspar in some leucocratic rocks.

It is certain that these criteria are not definite enough to enable one to decide, in every case, to which suite a given rock belongs. Extreme instances, such as nepheline syenites and plagioclase basalts, can be placed in one category or the other without difficulty, but there are many rocks of granitic to dioritic composition which are neither definitely alkaline nor unmistakeably alkalicalcic, and one is left without any means of classifying them. This at once condemns the proposal for systematic use. As for the claim that the two contrasted rock suites are connected with essentially different geological events, and that they are characteristic of regions of " Atlantic " and " Pacific " structure respectively, this is not clearly borne out by the facts.

It is not denied that the folded belts of the earth's crust are characterised by the predominance of rocks, such as granodiorite and diorite, andesite and basalt, which come within the definition of " alkalicalcic " rocks. But among these, close geological examination rarely fails to bring some typical alkaline rocks to light. Thus P. D. Quensel has found alkaline rocks in the Patagonian Cordillera, and J. A. Douglas has discovered them in the Andes of Peru. R. A. Daly and C. W. Drysdale have both described occurrences of highly alkaline rocks in British Columbia. Nepheline-bearing rocks in Alaska, Eastern Siberia, Korea, Manchuria and China, and leucitic lavas in Japan and the East Indies, are hard to reconcile with the theory which would restrict such rocks to regions of " Atlantic " structure.

On the other hand, the alkalicalcic lavas of the Deccan and Abyssinia are in faulted but unfolded plateau regions; the alkaline lavas of the Rift Valleys of East Africa are associated with olivine-basalts; and in Ascension and St. Helena, the same volcanoes seem to have emitted both alkaline trachytes and alkalicalcic basalts. Evidence of this kind can be multiplied greatly; it all goes to show that the generalisation which connects the two suites of rocks with particular geological structures or geographical regions is not universally true. Truly alkaline rocks are scarce in all parts of the world, but probably no scarcer in the comparatively little-known Pacific lands than in the world as a whole. It is clear, in any case, that the above generalisation, although it contains an element of truth, is subject to too many exceptions, and the two suites of rocks are defined in too general terms, to have any value at present in the classification of rocks.

The mineralogical composition of rocks as an aid to the understanding of the magma-system. It is easy to convince oneself that a knowledge of the *phases,* or mineral species, developed by a body of magma in the act of crystallising, is much more informative, as regards the physical and chemical conditions that prevailed in the magma, than any of the characters which we have considered in the foregoing pages.

In the first place, it is obvious that when the phases have been identified, they tell us what the components of the system are; and if we can determine the relative abundance of the phases, we can compute the ultimate chemical composition of the system.

The practical difficulties of this procedure are these: that some rocks are partly or wholly glassy and one has no means of judging the composition of the glass without analysing it; that most minerals are not simple compounds, but solid solutions, the precise composition of which cannot in general be deduced by any purely physical method; and that great accuracy is hardly attainable in the determination of the proportions of minerals on account of their intimate intergrowths, and for other reasons.

In spite of these limitations, it is sometimes possible to deduce the ultimate chemical composition of a rock with remarkable accuracy from careful measurement of the proportions of the constituent minerals, combined with exact determination of their optical constants. As an illustration of the degree of success which is attainable in this matter, we shall quote an investigation by J. P. Iddings of the granite of Butte, Montana. The minerals present in the rock are quartz, orthoclase, plagioclase, biotite, hornblende, pyroxene, magnetite, pyrite; and their proportions were determined by the method of linear measurement of thin sections. The average composition of each mineral is known; multiplying this in each case by the quantity concerned, Iddings estimated the chemical composition of the granite to be as in Column I. An actual chemical analysis of the rock, by H. N. Stokes, is quoted in Column II.

	I. *Calculated*	II. *Determined by Analysis*
SiO_2	64.83	64.34
Al_2O_3	16.42	15.72
Fe_2O_3	1.48	1.62
FeO	2.39	2.94
MgO	2.01	2.17
CaO	4.35	4.24

Na_2O	2.97	2.76
K_2O	4.11	4.04
H_2O	.67	1.01
Rest	.70	.97
	99.88	99.81

This is an extremely good agreement, much better, it must be said, than could be expected in every case. *It shows that it is possible to deduce the chemical composition of a rock from its mineralogical composition much more accurately than one can perform the reverse operation of deducing the mineralogical composition from a chemical analysis of the rock.*

While the chemical composition of a rock leaves us entirely in the dark regarding the physical conditions under which the magma crystallised, the mineralogical composition is full of information on this important matter. Every mineral has a definite range of temperature and pressure within which it is stable, and beyond which it transforms into something else. Several examples of such transformations were discussed in Chapter IV., for example, the inversion of α-quartz into β-quartz at 575°, and of β-quartz into tridymite at 870°; the splitting up of orthoclase into leucite and silica at 1170°, and that of enstatite into olivine and silica at 1625°. It is true that we do not know how far these inversion points are displaced by the presence of other substances, and particularly water, in the magma; but already we are in a position to set up a *relative temperature scale* for eruptive rocks, and to say that certain rocks completed their crystallisation below the α-quartz inversion point, and that others began to crystallise above the inversion point of enstatite. This is an important advance towards the physico-chemical classification of rocks.

Not only the temperature of crystallisation, but even the concentration of fugitive constituents in the magma may sometimes be deduced from the phases (minerals) that were formed in the rock. There are certain minerals which crystallise readily from dry fusion, and others which require for their production the presence of fluxes such as we described in Chapter III. The case of quartz has already been mentioned: it is a low-temperature mineral which transforms at 870° into tridymite. The latter mineral crystallises readily enough from anhydrous siliceous melts, and is well-known in fire-bricks, but quartz can only be induced to crystallise, in the laboratory, by the aid of fluxes. It has been

shown that the quartz crystals in many pegmatite veins have been formed at temperatures in the neighbourhood of 575°. Such pegmatites consist chiefly of quartz and alkali-felspars, hence we may write this down as a low-temperature or hydatogenetic association. Other minerals that are commonly found in the same association are muscovite, biotite, tourmaline and hornblende; all of these require the presence of fluxes for their formation, and we may add them all to the hydatogenetic series.

On the other hand, augite, olivine, anorthite and certain other minerals form readily in dry silicate melts, without requiring the presence of fluxes; they are pyrogenetic. The main members of the hydatogenetic and pyrogenetic series are named below.

Hydatogenetic	*Pyrogenetic*
Quartz	Anorthite, lime-rich plagioclase
Orthoclase, microcline	Pyroxenes, except ægirine
Albite	Olivine
Most amphiboles	Nepheline
All micas	Leucite
Garnets (except melanite)	Melilite
Ægirine	Tridymite
Tourmaline	Magnetite, ilmenite
Sodalite	Pyrite

A rock which consists entirely or very largely of hydatogenetic minerals, without glass, must have completed its crystallisation in the presence of a sufficiency of fluxes; on the other hand, if it consists mainly of pyrogenetic minerals, one is not entitled to assume that fluxes were lacking in the magma. But if a period of production of pyrogenetic minerals is followed by a period of production of hydatogenetic minerals, a progressive increase in the content of fugitive bodies is indicated. An example of this is the change from pyroxene production to amphibole-production which is often recorded in rocks of medium acidity. Pyroxene and amphibole are dimorphous forms of the same chemical compound or compounds, and whether the P-phase or the A-phase is formed must depend less on the chemical than on the physical conditions prevailing in the magma-system. Dimorphous phases do not form side by side except within a very narrow range of conditions, so the appearance of pyroxenes and amphiboles in the same rock must indicate a change of conditions, from those favourable to pyroxene forma-

tion to those favourable to amphibole formation. As a matter of observation, when both phases occur together, one of them is generally distinctly older than the other, and the common relation is that the pyroxene crystals have mantles of hornblende, or clusters of hornblende and biotite, around them, or else the hornblende crystals have residual cores of pyroxene at heart, clearly pointing to successive rather than simultaneous crystallisation of the two phases. Beautiful illustrations of these phenomena were given by J. P. Iddings in his description of the rocks of Electric Peak and Sepulchre Mountain in the Yellowstone National Park.

The precise conditions which determine the change from pyroxene production to amphibole production are not clearly understood, but there is some evidence to support the view that an essential condition is the increasing concentration of fugitive substances in the residual magma. J. P. Iddings showed that at Electric Peak the finer grained rocks carry hypersthene, those of slightly coarser grain hold hypersthene, augite and hornblende, and the most coarse-grained rocks hold hornblende and biotite only. A related observation was made by Harker in Carnarvonshire, where the typical fine-grained granophyres carry augite without biotite; the coarser granophyres and porphyries hold augite and biotite; and the granites have biotite alone. A connection between coarseness of crystallisation and abundance of fugitive constituents is so generally accepted as to be almost an axiom of petrology; if we accept that axiom we can scarcely doubt that the change from pyroxene-formation to amphibole-formation is controlled by the same factor.

If, on the other hand, hydatogenetic minerals are transformed into or succeeded by pyrogenetic ones, as hornblende by augite, a progressive decrease in the content of fugitive bodies is the probable cause. This condition is sometimes observed in lavas and dyke-rocks, from which the fugitive constituents were able to escape rapidly.

It should now be clear that, given the ability to interpret the evidence, the mineralogical constitution of a rock is capable of throwing light on many of the conditions, both chemical and physical, under which the crystallisation of the rock took place. Consequently, *the study and comparison of the mineralogical composition of rocks seems to offer the prospect of a harvest of important general propositions, based on the laws of physics and chemistry, such as would form the ideal basis for the classification of rocks.*

To this conclusion the answer may be made that mineralogical constitution has been the basis of classification from the earliest days of the science, with most unsatisfactory results. That is only partly true, for considerations of texture, geological occurrence, and even more irrelevant matters have been allowed to interfere with the application of the mineralogical method. But the chief reason for the present chaotic condition of rock classification is the lack of any definite system. As C. R. van Hise pointed out, in a sentence which we have already quoted, the only principle which petrographers have followed in the past has been to give a new name to every rock which is slightly different from any rock previously described, without reference to any plan.

To make matters worse, the names that have been longest in use, which were in the beginning mere popular names of the loosest kind, based on colour and other trivial characters, have gradually acquired the sanctity of "natural types," and these names have dominated all attempts at classification, instead of the classification dominating the names. Some of our most used names, like granite, porphyry, obsidian, and basalt, are of great antiquity; others, including gabbro, diabase, diorite, trachyte and phonolite, date from the beginning of the nineteenth century, when geology was still undecided whether such rocks were igneous or were chemical precipitates from the primeval ocean. The names have sometimes changed their meaning, but through all changes they have persisted and dominated every attempt at classification.

If we turn again to the philosophers, we may read that "our commonest title (for a thing), and the properties which this title suggests, have in reality nothing sacramental. They characterise *us* more than they characterise the thing. But we are so stuck in our prejudices, so petrified intellectually, that to our vulgarest names, with their suggestions, we ascribe an eternal and exclusive worth" (William James).

In short, the mineralogical classifications of the past have been unsuccessful because they showed a lack of recognition of the principles and purpose of classification as a science in itself. If we aspire to set up a physico-chemical classification of rocks, expressed in terms of minerals, we must first give up all bias in favour of existing rock-names and the ideas which they suggest. If an existing name for a supposed species of rock can not be made to conform to the boundaries of a new and well-reasoned

classification, it is not to be assumed that the method of classification is wrong; it is much more likely that the name is wrong, in the sense of having been given without due discrimination between like and unlike or essential and inessential.

REFERENCES.

Becke, F.—Tschermak's Min. Pet. Mitth., 1903.

Bowen, N. L.—Amer. Jour. Sci., 1914, *257*.

Cross, W.—Quart. Jour. Geol. Soc., 1910, *470*

Cross, W.; Iddings, J. P.; Pirsson, L. V.; Washington, H. S.—The Quantitative Classification of Igneous Rocks: Chicago, 1903.

do. Jour. Geol., 1906, *692*.

Daly, R. A.—(Composition) Proc. Amer. Acad.: Arts and Sciences, 1910, *211*.

do. —(Purcell Mts.) Festschrift H. Rosenbusch; Stuttgart, 1906.

Du Toit, A. L.—(Insizwa) Cape of Good Hope, Geol. Comm., 1910, *111*.

Harker, A.—(Atlantic rocks) Science Progress, 1897, *12*.

do. — do. Natural History of Igneous Rocks, 1909, *90*.

do. —(Carnarvon) The Bala Volcanic Series: Cambridge, 1889.

Hatch, F. H.—Text Book of Petrology, 1891-1926.

Iddings, J. P.—(Classification) Jour. Geol., 1898, *92, 219*.

do. —(Butte) Igneous Rocks, vol. I., 1909, *447*.

do. —(Electric Peak) U.S. Geol. Survey, 12 Ann. Rep., 1891, *569*.

James, W.—Text Book of Psychology, 1908, *354-7*.

Mill, J. S.—System of Logic, Bk. 4, chaps. 6, 7, 8.

Pirsson, L. V.—Amer. Jour. Sci., 1899, *271*.

Schofield, S. J.—Canada, Geol. Survey, Museum Bulletin 2, 1914.

Shannon, E. V.—Jour. Geol., 1919, *579*.

Van Hise, C. R.—Jour. Geol., 1899, *686*.

Washington, H. S.—(Tables) U.S. Geol. Survey, Prof. Paper 99, 1917.

do. —(Oxides) Proc. Nat. Acad. Sci., 1915, *574*.

CHAPTER VII.

A SYSTEM OF PETROGRAPHY.

Our immediate task, arising out of the discussion in the last chapter, must be to show how rocks can be grouped, on a mineralogical basis, in such a way that each group will convey the greatest possible amount of information about the physical and chemical history of the magma system.

With this end in view, it is essential that the quantitative element in petrography should receive more attention than it does in current classifications. The need for quantitative treatment of the subject has been more widely recognised in America than elsewhere, but a mistaken conception of the relative importance of analytical and of physical chemistry has had the unfortunate result that more weight has been attached to the bulk analysis of rocks than to the quantitative determination of the phases present in them. We have already seen that little or nothing can be deduced from a bulk analysis by itself, however carefully it is performed, regarding either the mineralogical constitution of the rock or the physico-chemical history of the magma which gave rise to it. One does not wish to detract from the value of the thousands of excellent rock analyses that have been made as a direct consequence of the American attitude towards rock classification; but petrology is something far greater than a mere branch of analytical chemistry.

The petrographer who describes a rock in qualitative terms, even if he adds a chemical analysis as a concession to the modern spirit, has left his job half done if he makes no attempt to correlate the mineralogical with the chemical characters of the rock by calculating the proportions of the phases. Chemical analysis of a rock is not an end in itself; its true place in petrography is to amplify and check the determinations made with the microscope. Microscopy is and will remain the primary method of petrography; but chemical analysis is the secondary method, and what a petrographer cannot learn by one method he must be prepared to ascertain by the other. The day will come when no description of a rock will be considered satisfactory which does

not include a quantitative statement of its mineralogical constitution; and if this cannot be made without the aid of chemical analysis, then it is the duty of the petrographer to seek that aid.

A systematist is therefore entitled to assume that in future the proportion, as well as the character, of every mineral present in a rock will be determined with some approach to accuracy.

The system proposed here does not depend on bulk analysis; it is a mineralogical classification throughout; but it demands the reasonably accurate determination of the quantity as well as the kind of every mineral present in a rock; and in respect of the felspars, which are the main constituents of all but the rarest types of rock, it demands a knowledge of the ratio of orthoclase : albite : anorthite. In all but the most fine-grained and hypocrystalline rocks the first requirement can be adequately met by geometrical rock analysis. For the second requirement, careful optical examination of the felspar, combined if necessary with physical and microchemical tests and geometrical measurements, will often obviate the necessity for bulk analysis. But if the necessary information cannot be furnished without partial or complete analysis of the rock, then the system proceeds on the assumption that such an analysis will be made.

The various factors used in the construction of the system will be discussed in turn.

(1)

The separation of eucrystalline from dyscrystalline rocks has already been discussed (page 112). It is held to be justified by the great differences in the physical conditions under which these two classes of rocks were generated.

(2)

Since silica is the largest component of all eruptive rocks (excepting only certain masses of small size in which oxidic or sulphidic ores have been abnormally concentrated) and especially since it predominates to an overwhelming extent over all other acidic oxides in the magma system, it requires no subtlety to see that *the way in which the silica is combined with the bases,* or the ratio of acidic to basic molecules, is about the most fundamental chemical character of the system.

A grouping of the rock-forming minerals in accordance with the degree of saturation of the bases with silica was discussed in Chapter V. Minerals were there described as saturated or unsaturated with respect to silica, according to whether they do or do not form side by side with quartz under such conditions as

prevail during the freezing of eruptive magma. According to the presence or absence of quartz and of unsaturated minerals respectively, we can establish the following groups of eruptive rocks (S. J. S., 1913) :—

I. Oversaturated rocks (*i.e.*, those which contain free primary silica);
II. Saturated rocks (containing neither free silica nor any unsaturated mineral);
III. Undersaturated rocks (*i.e.*, those which contain unsaturated minerals)—
  (a) With magnesia, lime or alumina unsaturated,
  (b) With alkalies unsaturated;
  (c) With alkalies and magnesia, lime or alumina unsaturated.

The dividing-lines between these groups are the boundary-curves of the chemical systems

silica—orthoclase—leucite
silica—albite—nepheline
silica—pyroxene—olivine
silica—anorthite—melilite
silica—muscovite—corundum

and of similar systems involving some of the less abundant minerals. Of these five systems, the first and the third have been studied in the crucible, and the results were discussed in Chapter V. Although numerical data are wanting for the other systems, there can be no doubt, in view of the evidence led in Chapter V., that these systems are similar to the others, although possibly less simple.

By using these boundary-curves in place of the vague and arbitrary dividing-lines of the Rosenbusch and earlier classifications, we not only express an important chemical character of the magma-system, but we are enabled to state positively, for each group of rocks thus delimited, that certain minerals are possible constituents of that group and that certain others are excluded. This is a great advance, in respect of definiteness, as compared to the older systems.

Fig. 20 (to which no quantitative meaning is to be attached) shows the five primary groups of rocks occupying their appropriate regions in a greatly simplified equilibrium diagram.

(3)

After silica, the component next in importance is alumina. One may speak of rocks as oversaturated or undersaturated with alumina, just as with silica, but the resulting groups are not so clear-cut as in the case of silica. An excess of alumina over soda, potash and lime in an oversaturated rock goes into muscovite, biotite, tourmaline, topaz, or iron-manganese garnet; in a quartz-free rock, it enters mica or corundum. A deficiency of alumina,

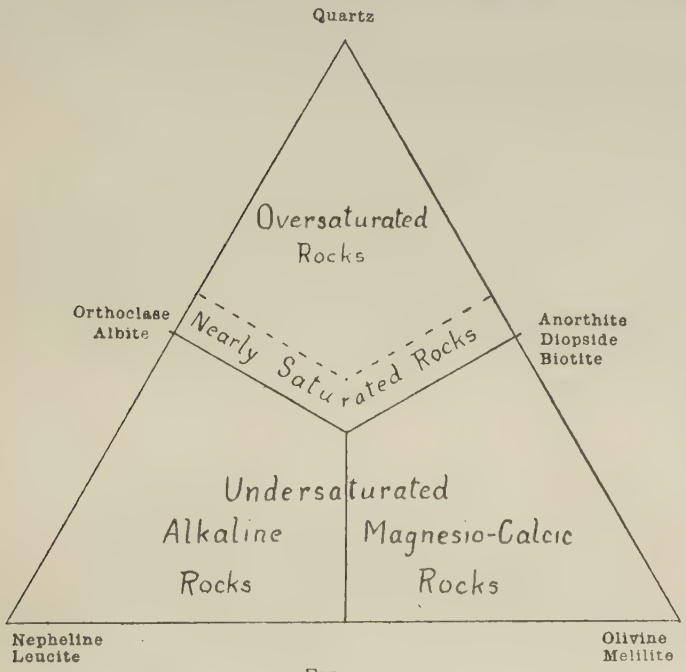

FIG. 20.

as compared to soda, potash and lime, is exhibited in two ways. If the deficiency is small, it affects the lime only, an amount of lime equal to the deficient alumina being compelled to assume the form of calcium metasilicate and enter into a pyroxene or a hornblende. If the deficiency of alumina is greater than the whole molecular proportion of lime in the rock, then all the lime goes into the metasilicate form, and some of the soda, having no alumina to combine with, must either unite with ferric oxide to form a soda-pyroxene or soda amphibole, or else form some less-common silicate such as ænigmatite, eudialyte or pectolite.

The matter is not really quite so simple as this, however, for the behaviour of certain minerals is anomalous. Biotite, which generally holds more magnesia and potash than alumina (molecular proportions are meant), is frequently associated with muscovite, in which alumina exceeds potash. Again, many augites and hornblendes actually carry up to 10 per cent, or even more of Al_2O_3; yet they must be regarded as indicating a deficiency of alumina in the magma, because the molecular proportion of alumina in these minerals is less than that of CaO and much less than that of CaO + MgO. These points illustrate the greater complexity of systems with variable alumina, as compared to those in which silica alone is variable. On account of this complexity it is not at present possible to classify rocks in a completely unequivocal way as oversaturated, saturated, or undersaturated with alumina. For practical purposes, however, we shall commit no very grave error if we consider all metasilicate-bearing rocks to be undersaturated with alumina; all muscovite-bearing rocks to be oversaturated with alumina; while the biotite-bearing rocks may be reckoned to the latter class if the biotite is alone or accompanied by muscovite, but to the former class if it is accompanied by metasilicates.

These relations are illustrated graphically in the simplified equilibrium diagram of *Fig.* 21, in which the silica co-ordinate is supposed to stand at right-angles to the paper. Briefly, the following groups of rocks stand out as chemically distinct :—

(a) A *peraluminous* group, characterised by primary muscovite, biotite, corundum, tourmaline, topaz, almandine, or spessartite.

(b) A *peralkaline* group, characterised by soda-pyroxenes or soda-amphiboles, eudialyte, ænigmatite, etc., and by the virtual absence of anorthite. (It is doubtful whether anorthite is entirely absent; several descriptions of peralkaline rocks mention " albite-oligoclase " in association with ægirine, and a little anorthite is present in anorthoclase. It may be that alumina is shared between soda and lime, the former taking the lion's share, but the lime also securing enough to form a little anorthite which is then drowned in an excess of albite.)

(c) A group characterised by common pyroxenes, amphiboles, olivine, fayalite, or epidote, with or without the addition of biotite.

The last group contains two fundamentally different mineral associations, namely, the hornblende-biotite-epidote association; which is hydatogenetic, and the orthopyroxene-clinopyroxene-olivine association; which is pyrogenetic. We have already seen that the succession of a period of pyroxene production by one of amphibole production is probably a normal event in the cooling of many magmas. Such a transformation, affecting two of the most

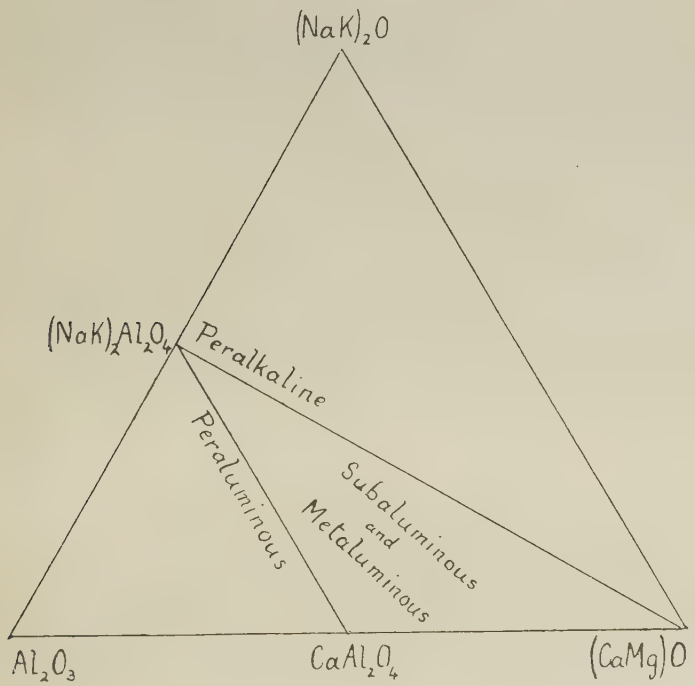

FIG. 21.

important families of rock-forming minerals, is important enough to be recognised in classification, so we split up the last group into two, as follows:—

(c_1) A *metaluminous* group, characterised by any of the following associations: hornblende-biotite, hornblende-augite, biotite-augite, hornblende-biotite-augite; or by hornblende alone, or by primary epidote with or without hornblende or biotite. Olivine may also be present.

(c_2) A *subaluminous* group, characterised by pyroxenes or olivine, without appreciable quantities of hornblende, biotite, or primary epidote.

In the case of a glassy rock, it is generally possible to recognise the chemical type if a good analysis is available. The possible mineral composition must be calculated, and for this purpose the rules that regulate the calculation of the norm in the American Quantitative System are suitable. Any deficiency of alumina as compared with alkalies in the rock will cause acmite to appear in the norm, thus indicating that the rock is peralkaline. If corundum appears in the norm, without hypersthene, the rock is of necessity peraluminous; while total absence of normative corundum will generally indicate that no mica or hornblende could have been formed by the crystallisation of this rock, and the rock must be referred to the subaluminous type. Should the norm contain both corundum and hypersthene, then a little calculation is necessary to show whether the ratio between these two molecules is about the same as in biotite (usually 1 : 1, though sometimes nearly 1 : 2), or whether there is an excess of hypersthene over the proportion needed to form biotite. In the former case the rock may be considered as a potential biotite-bearing variety (peraluminous type); in the latter case an aluminous pyroxene or amphibole might form, and the rock should be considered metaluminous. It may be added that calculations of this kind are worthless unless the analysis is above suspicion; particularly as regards the determination of alumina.

(4)

Since the remaining metallic oxides in eruptive rocks, with the single exception of iron oxide, are only found in the form of silicates or aluminosilicates (and very sparingly as aluminates, titanates, phosphates, carbonates, or fluorides), it follows that variations in the proportions of these oxides can not be separated from the variations of alumina or silica. So long as no change takes place in the degree of saturation of the bases with alumina and silica, any variations in the proportions of these bases can only affect the *relative abundance* of the minerals that are formed. Thus much potash or little potash in the magma simply means much orthoclase or little orthoclase in the rock; much magnesia or little magnesia means much metasilicate or little metasilicate; and so on. In no case does a new phase appear on account of

the variation of the oxide concerned, so long as the degree of saturation with silica or alumina remains unaffected.

Iron oxide is an exception, for Fe_2O_3 (hematite) is found in some rocks, and Fe_3O_4 (magnetite) in almost all. In many lavas, the production of hematite or magnetite is the result of atmospheric oxidation of other iron compounds, but it is not clear what it is that determines the distribution of iron between oxide and silicate in deep-seated eruptive rocks and pegmatite. It seems to follow, from the almost universal occurrence of magnetite, that its appearance does not depend in any direct way on the fluctuations of the other basic oxides in the magma.

To express the variations of soda, potash, magnesia, lime, and iron oxides within the groups already established by the degree of saturation of the rock with silica and alumina respectively, there is no means available, except *either* a quantitative mineralogical analysis *or* a quantitative chemical analysis of the rock in question. If the latter method is chosen, then a suitable mechanism of classification already exists in the Quantitative Classification of Cross, Iddings, Pirsson and Washington. If, on the other hand, it is desired to retain a mineralogical basis of classification throughout, then it will be necessary to devise a method of sub-dividing each of the " saturation groups " on arithmetical lines, according to the proportions of the dominant minerals. As a first step in this direction it may be sufficient to state simply the *ratio of light to heavy minerals* in the rock. If we make 2.8 the critical density, then the light minerals are quartz, all felspars, all felspathoids (including analcime and cancrinite) and calcite. These are all free from magnesia and iron, and are consequently pale in colour. Minerals that are denser than 2.8 are nearly all dark coloured on account of the presence of ferrous or ferric oxide. The ratio of heavy to light minerals is therefore essentially the ratio of dark to pale coloured minerals, and since it is this which determines the colour of the rock as a whole, it may conveniently be called the colour ratio. [In practice, if a rock contains 17 per cent. of heavy minerals, we shall say that its *colour ratio* is 17 per cent., or that its *colour index* is 17.]

The majority of rocks have less than thirty per cent. of dark minerals, but quite a number carry between thirty and sixty per cent. Beyond the latter figure there is rather a rapid passage to rocks consisting entirely of dark minerals. It will be found most convenient, and most nearly in accordance with existing practice

(as seen in the giving of current rock names), to establish *four* primary divisions according to the value of the colour ratio. They may be as follows :—

(1) Rocks holding less than 30 per cent. by volume (or about one-third of their weight) of dark minerals; such rocks may be described as *leucocratic* or predominantly light coloured. (Term due to W. C. Brögger.)

(2) Rocks holding more than 30 per cent. but less than 60 per cent. by volume (roughly one-third to two-thirds of their weight) of dark minerals; these rocks may be termed *mesotype*. (A. Lacroix and others use the form " mesocratic," but this has a nonsensical meaning and ought not to be perpetuated.)

(3) Rocks holding from 60 per cent. to 90 per cent. (roughly the same by weight) of dark minerals; these may be described as *melanocratic* or predominantly dark-coloured. (Term due to W. C. Brögger.)

(4) Rocks holding more than 90 per cent. by volume of dark minerals. For such rocks a special name (perknite) is already in use.

We must also recognise the existence of rocks which are distinguished by the practical absence of all dark minerals. A. Lacroix describes such rocks by the adjective " holo-leucocratic "; it should be sufficient in general to use the prefix leuco-, as in leuco-granite.

(5)

The light minerals in eruptive rocks are sometimes unsaturated (felspathoids), but far more frequently saturated (felspars). The great majority of rocks contain some kind of felspar, which is also by far the largest constituent of most of them. On this account, some further sub-division is needed, in addition to that afforded by the degree of saturation with silica. The custom of the present time is to separate rocks in which alkaline felspars predominate from those in which plagioclase is dominant, and to make a third division for rocks in which orthoclase and plagioclase are about equal.

But since " orthoclase " includes varieties that are rich in soda, and plagioclase means anything from pure soda-felspar to pure lime-felspar, the practice is not good chemistry; and since soda appears in both terms of the ratio, it is not even good arithmetic. The weakness of this method of classifying rocks is shown by the contradictions to which it gives rise. For instance,

a lava of San Mateo Mountain, New Mexico, which was named "andesite" by J. S. Diller, has the following composition:—

quartz	5.5 per cent.
orthoclase molecules	30.0
albite molecules	54.0
anorthite molecules	2.2
dark minerals	8.8

This rock carries more plagioclase than orthoclase, so the use of the name andesite is justified by current practice; but the proportion of pure potash felspar is more than thirteen times that of anorthite.

In H. H. Robinson's admirable description of the lavas of San Francisco Mountain, Arizona, the names dacite and latite are employed. According to the accepted definitions of these names, latite contains roughly equal quantities of orthoclase and plagioclase, while dacite has plagioclase in considerable excess of orthoclase. Yet the chemical analyses of these lavas show that, in the dacites, orthoclase molecules are from one and a quarter to two and a half times as plentiful as anorthite molecules; while in the latite the reverse is the case.

These examples show that the statement of the ratio of plagioclase to orthoclase, which is conveyed by such names as latite, dacite, andesite, to which we may add monzonite, diorite and granodiorite, *as these names are currently defined,* is worthless as a guide to the relative proportions of potash, soda, and lime in the felspars. If much albite is present, plagioclase will exceed orthoclase even when the proportion of anorthite is quite small; and if little albite is present, orthoclase may exceed plagioclase, although the rock actually contains more anorthite than in the last case. Stranger still, if there is much albite and little anorthite, then the plagioclase approaches the composition of pure albite; under these circumstances it is no longer considered to be plagioclase at all, but is generally removed to the other side of the equation to swell the total of "alkaline" felspar.

These complications, which arise from the haphazard use of two ill-defined terms (alkaline felspar or "orthoclase," and "plagioclase") can only be avoided by discussing the felspars in terms of the pure components, orthoclase, albite, and anorthite, instead of their mixtures. In *Fig. 22* the three corners of the triangular diagram represent 100 per cent. Or, 100 per cent. Ab, and 100 per cent. An respectively. The Or-Ab-An field can be divided up in many ways, but the way that immediately and

strongly suggests itself is to demarcate a potassic field (Or-xzy), a sodic field (Ab-xzw), and a calcic field (An-yzw), all of them equal in area. Every rock that is represented by a point in the potassic field contains more orthoclase than either albite or anorthite, though not necessarily more than albite and anorthite combined. Similar statements can be made for the sodic field and for the calcic field.

It is well known that potash-lime felspars are not found in nature, and that mixtures of orthoclase and anorthite are always

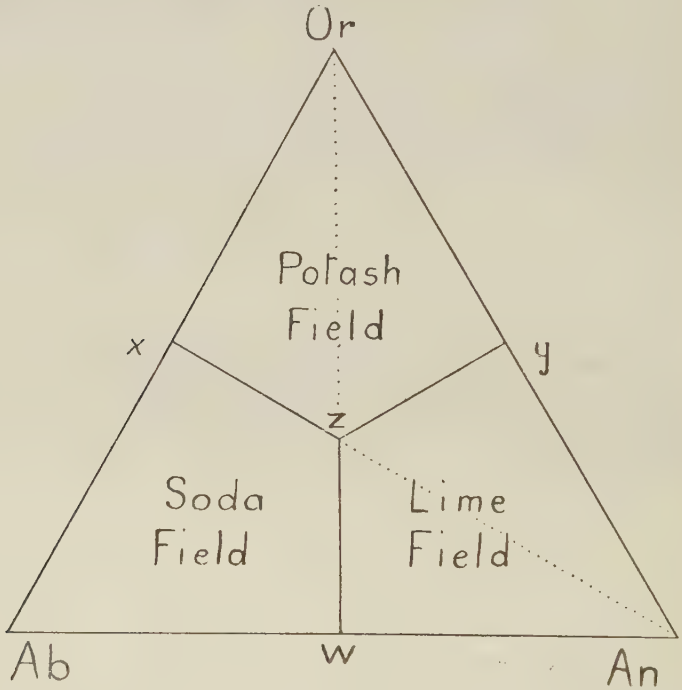

FIG. 22.

diluted by much albite. This means that the area Or-z-An in *Fig.* 22 is almost unrepresented, and that the potassic and calcic fields are each reduced in practice to almost half their theoretical area. The sodic field, however, is fully represented, for rocks are known which carry much albite and orthoclase with almost no anorthite, and others that have albite and anorthite, with only a minimal quantity of orthoclase; there are also many rocks in which all three components are present in considerable amount.

In further illustration of this point, see *Fig.* 23, which gives the composition of over 900 natural felspars, as computed by H. L. Alling. It will be advantageous, therefore, to sub-divide the large sodic field into a potash-soda section and a soda-lime section, as in *Fig.* 24.

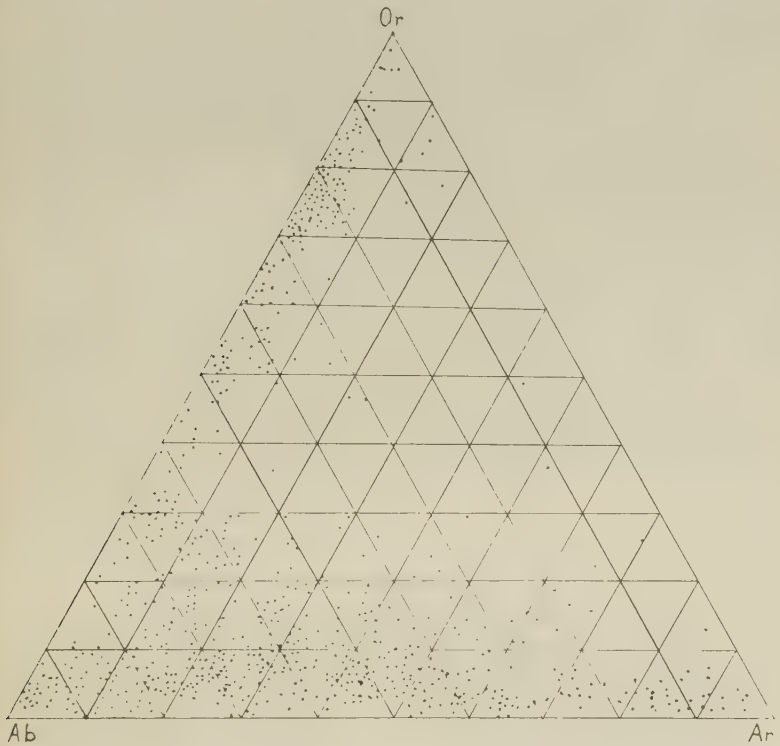

FIG. 23. The composition of 954 natural felspars expressed in terms of Or, Ab, and An. (After H. L. Alling.)

We have now divided the useful part of the triangle into four approximately equal fields, which are characterised mineralogically by potash-soda felspar, soda-potash felspar, soda-lime felspar, and lime-soda felspar respectively. The fields are defined in quantitative terms as follows :—

$$\text{Or} > \text{An} \begin{cases} 1.\ \text{Or} > \text{Ab} \text{ (potash-soda field)} \\ 2.\ \text{Or} < \text{Ab} \text{ (soda-potash field)} \end{cases}$$

$$\text{Or} < \text{An} \begin{cases} 3.\ \text{Ab} > \text{An} \text{ (soda-lime field)} \\ 4.\ \text{Ab} < \text{An} \text{ (lime-soda field)} \end{cases}$$

To classify rocks, on this basis, is not much more difficult than it is under any existing system, for all good petrographic descriptions include either optical or chemical determination of the composition of the felspars present. The first step will be to compare orthoclase to anorthite; in most rocks there will be a clear excess of one or the other, and as soon as that has been ascertained, a provisional name can be given to the rock. The ratio of orthoclase to albite will also be afforded by mere inspec-

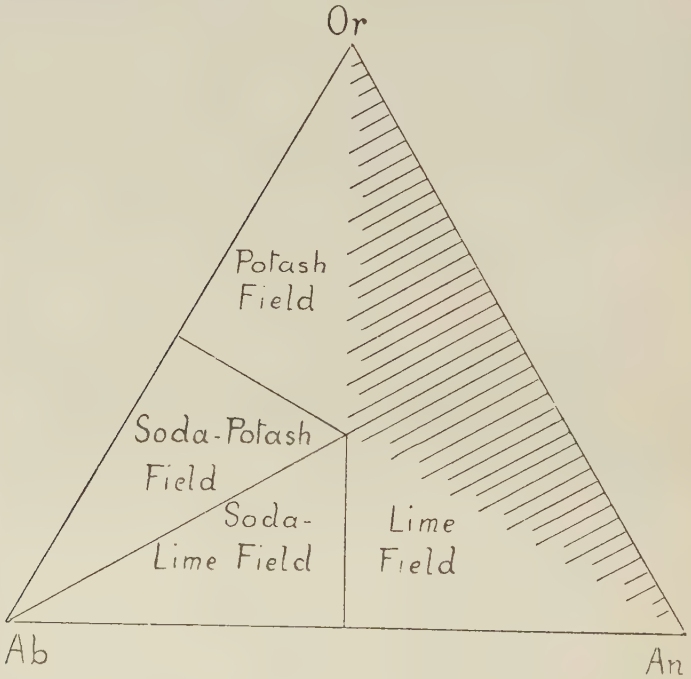

Fig. 24.

tion, in some cases; but in doubtful instances it will be necessary to undertake a closer investigation of the composition of the felspar, using either gravitational, optical, or chemical methods, all of which are already part of the routine of petrography.

* * * *

We have now provided for the erection of the following groups, each of which has a more or less definite physical or chemical significance :—

Two groups based on the degree of crystallisation;
Five groups based on the relation of silica to the bases;
Four groups based on the relation of alumina to the bases;
Four groups based on the proportion of light to heavy minerals;
Four groups based on the composition of the felspar.

We are now ready to proceed to the discussion of the larger groups of rocks; and in the course of this discussion we shall see to what extent, and in what direction, further sub-division is necessary or desirable within the groups.

REFERENCES.

Alling, H. L.—Jour. Geol., 1921, *294*.
Diller, J. S.—U.S. Geol. Survey, Bull. 148, 1897, *185*.
Robinson, H. H.—U.S. Geol. Survey, Prof. Paper 76, 1913.
Shand, S. J.—Geol. Mag., 1913, *508*; 1917, *463*

CHAPTER VIII.

THE OVERSATURATED ROCKS.

PART I. GENERAL.

The oversaturated rocks are those which contain an excess of silica over the available bases, that excess crystallising out either as α- or β-quartz or rarely as tridymite. In glassy rocks, the presence of an excess of silica can only be proved by calculation from the data furnished by chemical analysis.

Most oversaturated rocks are distinctly, or even highly, leucocratic, and contain more felspar than anything else, so it is not unreasonable that the first mineralogical sub-division of the group should be based on the composition of the felspar. If we apply the orthoclase : albite : anorthite ratio in the way that was described in the last chapter, we can immediately separate the rocks which are richer in orthoclase from those which are richer in anorthite. To the former we give the group-name of *granite*, if eucrystalline, or *rhyolite* if dyscrystalline. For the group richer in anorthite the corresponding group-names are *tonalite* and *dacite*. By the further application of the same ratio, we can distinguish accurately between potash-granite and soda-granite; potash-rhyolite and soda-rhyolite; and between soda-tonalite and lime-tonalite; soda-dacite and lime-dacite. Mesotype members of the group are few, and melanocratic members are scarcely known at all, so no new names are needed for these.

Armed with these group-names, and deferring further subdivision to a later occasion, we can proceed at once to discuss some important general aspects of oversaturated rocks.

The geology of the oversaturated rocks. It is generally held that oversaturated rocks are much more abundant, in the outer layers of the earth-crust at least, than any other class. In most countries, the data for testing this belief statistically have not been gathered together, but we owe to R. A. Daly a valuable computation of the areas occupied by outcrops of different kinds of eruptive rocks in the United States of America. For obvious reasons, no comparison of volumes is possible. Out of 6,607

square miles occupied by plutonic rocks, 5,932 square miles, or ninety per cent., consist of oversaturated rocks, mostly granite. In contrast with this enormous development of oversaturated plutonic rocks, the comparative scarcity of oversaturated lavas is surprising. Daly's figures show that out of 9,715 square miles of lava in the United States, only twenty-three per cent. are oversaturated. This is a point of great significance for the theory of petrogenesis; it suggests, and indeed goes far to prove, that the extrusion of a particular type of lava is not necessarily connected with the intrusion of a plutonic rock of the same chemical and mineralogical character.

Granite and tonalite occur in the form of enormous dome-like intrusions—so-called batholiths—whose upper surfaces may be exposed over hundreds of square miles. The batholith of Boulder, Montana, has an area of one thousand square miles; and the largest batholith in the Appalachian Mountains measures three hundred and fifty miles by fifty. In the Cape of Good Hope, a granite of nearly constant characters comes to the surface in one dome after the other, throughout an area measuring at least a hundred and fifty miles by fifty. In the Coast Range of British Columbia, and again in Patagonia, there are chains of batholiths, largely formed of granitic rocks, extending in each case for more than eight hundred miles parallel to the coast and from fifty to one hundred miles inland.

The thickness, or downward extent, of a batholith is quite uncertain, but as no case is known in which erosion has exposed the floor of a really large intrusion, the thickness is certainly to be expressed in miles. It is most unlikely that any of the greater intrusive bodies rests on a floor of sedimentary rocks, but " what underlies the granites " is one of the problems that petrology has still to solve. According to a view which finds many eminent supporters, granite is itself only the differentiated skin or crust of an underlying basaltic world-magma.

The margin of a large granite intrusion is sometimes sharply defined and more or less plane, and one can lay a knife blade along the contact so that all rock on one side of the blade is eruptive, all on the other side sedimentary. Such a junction may be seen, for example, between the granite and the " killas " on the north side of Cape Cornwall in England; in this case the granite retains its coarse grain right up to the margin, and the only textural change to be noticed is that along the margin the larger felspar crystals of the granite have placed themselves per-

pendicular to the bounding surface. At Hörtekollen, in the Christiania district, there is an equally sharp contact, but the granite becomes fine-grained towards the margin. The contact of granite with Silurian limestone at Konerudkollen is said by W. C. Brögger to be " haarscharf " (hair-sharp).

A different type of junction is sometimes seen, especially in regions of intense metamorphism; it is characterised by the absence of any sharp bounding surface. The appearance in such a case is as if the country rock had soaked up the liquid magma like a sponge, being itself at the same time partly dissolved and incorporated in the magma. In crossing such a junction one passes insensibly from pure granite to granite holding dark bands and streaks of half-incorporated sediment; from this to an intimate mixture of sediment and granite; then to sedimentary rock containing veinules of granite, or isolated, large felspar crystals; and eventually to sediment which has been affected by the physical conditions prevailing at the contact, but which has received no accession of material from the magma. The streaky or banded rocks which result from this kind of intrusion are known in general as " gneiss," and the various degrees of admixture are often indicated roughly by the use of such terms as " gneissose granite " or " granite-gneiss " for those in which granitic material predominates, and " injection-gneiss " or " migmatite " (*i.e.*, mixed rock) for those consisting to a large extent of foreign material. Many of the oldest and largest granite intrusions in all parts of the world have this gneissose character in part, and it is usual to call them either granite or gneiss indifferently. Much of the " Laurentian " of Canada, the " Lewisian " of Scotland, and the " Old Granite " of South Africa consists of such hybrid material. The granite contacts of the Pyrenees, described by A. Lacroix in a set of admirable memoirs, belong to this type, as do those of the younger and older granites of Finland, which have been described by J. J. Sederholm.

Among smaller intrusions—stocks, laccolites, sills and dykes—a notable degree of differentiation, or variation from point to point, is often observed. This commonly takes the form of a transition from oversaturated rock, in the upper part of the intrusion, to saturated and undersaturated facies at lower levels. An illustration of this effect, on a grand scale, is furnished by the Ilimausak batholith of West Greenland, which, according to N. V. Ussing, consists of granite on top, passing downwards into syenite and nepheline-bearing rocks. In the laccolitic intrusion of

Loch Borolan, Scotland, a very leucocratic granite passes downwards into quartz-free syenite, then into melanite- and nepheline-bearing rocks. The great saucer-shaped intrusion of Sudbury, Canada, has over twenty per cent. of quartz in its upper layer, which is a soda-granite; passing downwards, quartz and alkali-felspar gradually give place to labradorite and hypersthene, and the rock becomes a norite (A. P. Coleman). In the Insizwa sheet in South Africa, which has been described by A. L. du Toit, the upper levels of the sheet contain quartz and the lower levels olivine. This relation is also observed in the sill described by W. A. Bayley and R. A. Daly at Pigeon Point, Minnesota. The main part of this intrusion is olivine-gabbro, but the upper layer, forming one-eighth of the whole thickness of the sill, is red soda-granite.

In other cases, a body of dioritic or gabbroic rock, which has little or no excess of silica, has developed irregular veins and pockets of coarse-grained granite which merge quite gradually into the surrounding rock. T. A. Jaggar described such granite-pegmatites in diabase (dolerite) near Boston, Mass. "Approaching one of the veins, the long white plagioclase crystals of the diabase are seen to acquire a salmon-coloured border zone of more acid felspar; gradually the plagioclase gives place to microcline, and the long laths are replaced by short, rectangular pink prisms; quartz replaces all the bisilicates and in places the rock appears like a granite." Thin sections of these rocks show a perfectly gradual passage from normal diabase through quartz-diabase to quartz-microcline pegmatite.

In stocks, pipes, and dykes the differentiation often proceeds in a lateral direction. Thus a small stock of syenitic rocks at Almunge, Sweden, which was described by P. D. Quensel, shows a highly oversaturated margin with a saturated and partly undersaturated interior. A similar arrangement of successive zones is exhibited, according to G. A. Young, by the rocks of Mount Yamaska, one of the Monteregian Hills of Quebec. V. M. Goldschmidt has described dykes at Konnerudkollen, Norway, which have a centre of granite or granite-porphyry and selvages of diabase. The Brefven dyke, south of Lake Hjalmaren, Sweden, is a fine example of such a mixed dyke (*Fig.* 25). It shows a gradation from olivine-diabase through intermediate facies of greater and greater acidity to a micrographic granite (A. G. Högbom).

It is not always clear in such cases whether the process of

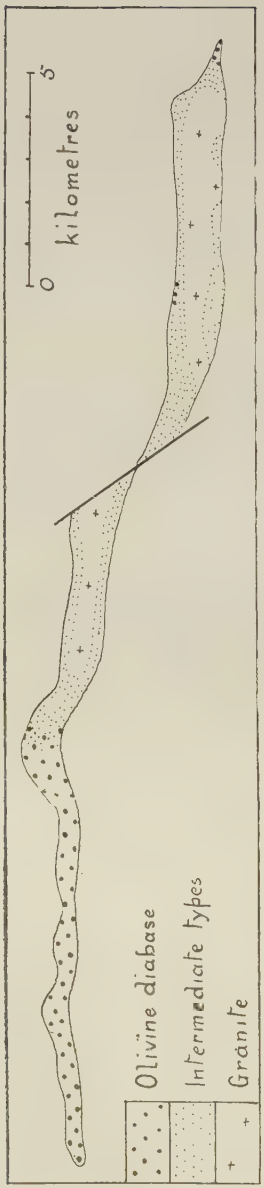

FIG. 25. Plan of the Brefven dyke, Sweden, showing passage of olivine-diabase (dolerite) through intermediate types into granite. (After K. Winge.)

differentiation or splitting of the magma, which led to the production of these different kinds of rock, took place before or after the intrusion of the magma into the position in which it finally solidified; but the significance of the association is almost equally great in either case, for it shows that at some level in the crust, whether higher or lower, a splitting of magma into more and less acid portions took place. *It is beyond doubt, therefore, that some oversaturated magma is of "derived" origin, that is, that it is produced by the differentiation of other magmas.* Whether one should go further and regard all granitic magma, and therefore all oversaturated rocks, as differentiation products of more basic magma; or whether in view of the immense bulk of the oversaturated rocks, one should admit the existence of a "primordial" granitic magma, is one of the fundamental questions to which petrology has yet to furnish an answer.

The mineralogy of the oversaturated rocks. The proportion of quartz in an oversaturated rock ranges from almost nothing to a maximum which, in certain low temperature pegmatite veins, approaches 100 per cent. As we saw in Chapter I., there is no sharp line of division between an "igneous" granite and an "aqueous" quartz vein; but we have agreed that rock bodies which consist mainly of fibrous or prismatic quartz, with little or no felspar, shall not be regarded as eruptive rocks.

With this restriction, it may be said that the quantity of quartz that is to be found in unaltered eruptive rocks seldom exceeds fifty per cent.; and of what we may call average granite, quartz forms between twenty-five and forty per cent.

The crystals of quartz in plutonic rocks are sometimes enclosed in the outer zones of the felspar crystals, but the bulk of the quartz occupies the interstices between the felspars and the other constituents, and it is certain that in all deep-seated rocks quartz is one of the last minerals to crystallise. It has been shown by Day, Sosman and Hostetter that quartz undergoes a remarkably rapid contraction below 575°; from this point down to 500°, the contraction amounts to 2.4 per cent. of the volume of the quartz. This must be an important cause of the production of shrinkage cracks in granites, and it explains why residual veins are especially characteristic of oversaturated rocks.

Tridymite, which is the stable form of silica between 870° C. and 1470° C., has not been recognised in deep-seated rocks, but it is found in some lavas, and also in foreign rock-fragments which have been enveloped in lava and baked by its heat. Minute hexagonal plates of tridymite are sometimes seen in cavities in porous lava, and it is likely that this mineral, as well as the still rarer cristobalite, has been formed by some special reaction in which hot gases took part, and that it is not a direct product of the magma at all. A. Lacroix holds that tridymite has been formed, in the lavas of Mount Pelée, by transformation of the glassy base of the rock, probably under the influence of water vapour. J. P. Iddings has formed the same opinion regarding the tridymite in the rhyolites of the Yellowstone Park. Emmons and Larsen, describing the tridymite-rhyolites of Colorado, say: "It seems likely that in the final fluid part of the magma the silica and associated mineralizers were in chemical combination, and that on the breaking up of these compounds the tridymite was deposited, and the volatile constituents released, thus forming the gas cavities. . . . It may easily be that the composition of the so-called mineralizers largely determines the form in which the silica is deposited." In the San Juan region of Colorado, tridymite makes up from one-fifth to one-third of some of the rhyolites.

Although the characteristic mineral of the oversaturated rocks is quartz, the most abundant mineral is certainly felspar. This is usually a moderately potassic kind, either orthoclase (microcline), soda-orthoclase, or microperthite. A plagioclase felspar,

ranging in composition from albite to labradorite, is sometimes present to the almost complete exclusion of orthoclase; but potash felspar, whether free or held in solid solution in the outer zones of the plagioclase crystals, is never wholly absent. There is a distinct relation between the amount of quartz and the amount of potash felspar present in a rock. As the plagioclase becomes more and more calcic, quartz dwindles, and when anorthite exceeds albite in the plagioclase then there is seldom more than a trace of quartz left. Thus in the labradorite- and bytownite-bearing rocks (gabbro, anorthosite, etc.) oversaturation is not a common condition.

The antipathetic variation of quartz and orthoclase is well illustrated by the following series of analyses of closely related rocks from Idaho (W. Lindgren) and from the Purcell Mts., British Columbia (R. A. Daly).

Idaho (W. Lindgren)

	(1)	(2)	(3)	(4)
Quartz	29.2	28.04	25.00	8.45
Or	18.07	15.84	11.21	7.57
Ab	27.19	33.54	30.25	26.20
An	9.53	11.15	13.88	20.45

Purcell Mts. (R. A. Daly)

	(1)	(2)	(3)	(4)
Quartz	22.8	11.7	6.3	4.0
Andesine ...	18.5	16.5	—	—
Labradorite	—	—	25.6	34.8

Duparc and Borlioz go so far as to maintain that the association of calcic plagioclase (labradorite to anorthite, without mantles of more sodic felspar) with much quartz, demonstrates that the rock containing these minerals is not a simple magmatic product. They have described various rocks from Bolivar, which hold quartz, basic labradorite, diopside and hornblende, and which might pass for tonalites, although they have actually been formed by reaction between granite and limestone.

The great variation that may be found in the composition of the felspar in different parts of one continuous body of " granite " is shown by the following table, compiled by W. J. Sollas, relating to the soda-granite of the Wicklow Mountains, Ireland.

Croghan Kinshela ...	1	part orthoclase	to	25	parts	albite
Rockabill	1	,,	,,	,, 1.2	,,	,,
Blackstairs	1	,,	,,	,, 1.1	,,	,,
Poulmounty	1	,,	,,	,, 1.2	,,	oligoclase
Three Rock Mountain	1	,,	,,	,, 1.2	,,	,,
Carnsore	1	,,	,,	,, 1.4	,,	,,
Ballinaclash	1	,,	,,	,, 3.9	,,	,,
Aughrim	1	,,	,,	,, 5.3	,,	,,
Ballyknockan	1	,,	,,	,, 1.2	,,	andesine
Ballinamuddagh	1	,,	,,	,, 1.6	,,	,,
Coolboy	1	,,	,,	,, 3.9	,,	,,
Cushbawn	1	,,	,,	,, 5.1	,,	,,

Since felspar makes up the greater part of all oversaturated rocks, the arrangement of the felspar crystals mainly determines the texture of the rock. We have to recognise three principal varieties of texture, as follows :—

(1) The crystals are large, but often unequal in size, and are closely packed together, without definite arrangement. Quartz and mica scales occur in the interstices, and the smaller mica scales are often enclosed in felspar. Owing to the mutual interference of the felspar crystals, only a minority of them have developed their ideal shape. This is ordinary "granitic texture," and is characteristic of the majority of plutonic rocks of all kinds.

(2) The felspars are more tabular in shape, owing to the large development of the pinacoids, and they and the mica scales or hornblende needles are arranged in roughly parallel position.

(3) Many granitic rocks are more or less distinctly porphyritic, having large insets of orthoclase or microcline in a groundmass of smaller felspars, quartz and mica. The felspar of the groundmass is sometimes different from that of the insets; thus in the well-known porphyritic granite of Shap Fell, Westmorland, the large insets are pink orthoclase and the felspar of the groundmass is white oligoclase.

The *dark constituents* of oversaturated rocks include white and black micas, various kinds of hornblende and pyroxene, tourmaline, garnet and topaz. Sphene, zircon, apatite, fluorspar and magnetite are usually present in small quantity, and so, at times, are pyrite and other sulphides. Fayalite (iron olivine) makes an occasional appearance in oversaturated lavas, and beryl, eudialyte, astrophyllite, allanite, and other minerals which contain the oxides of the rare metals are often detected in the soda-

rich granites. Andalusite, cordierite and sillimanite are not normal minerals of eruptive rocks, and when they appear in granite there is always reason to suspect that assimilation of aluminous sediments has taken place.

The mica of oversaturated rocks includes ordinary muscovite, the lithia-micas (lepidolite and zinnwaldite), and several varieties of biotite. Muscovite is seldom found in large quantity except in rocks with an abundance of free quartz, that is, in granites of a very acid type, and it is developed in large crystals in pegmatite veins. Lithia mica is almost confined to the aplitic and pegmatitic facies of the more acid granites, and to contact zones. Biotite is seldom entirely absent from quartz-bearing rocks; it is a deep brown variety, owing its colour to ferric oxide, but it becomes greenish with advancing alteration. The presence of minute enclosures of apatite, zircon, xenotime, allanite, and other scarce minerals is a peculiarity of the biotite in most granites. Round the enclosed grains, some of which are radio-active, the mica is generally more deeply-coloured than elsewhere, and in the hands of Prof. Joly these "pleochroic haloes" have afforded a means of measuring the age of the containing rock.

The quantity of mica in an eruptive rock seldom exceeds fifteen per cent.; in average granite it may be said to range from about three to ten per cent. Muscovite is generally subordinate to biotite, and it is only in some very acid granites and pegmatites that the relation is reversed. In lavas, mica is even scarcer than in the plutonic rocks; many rhyolites and dacites carry no more than a trace of biotite.

Green hornblende very often accompanies biotite in the plagioclase-bearing granites, especially the more calcic ones and it is frequently associated with pale green diopside. Ortho-pyroxene (enstatite or hypersthene) is occasionally present even in potassic granites and rhyolites, but only in small quantity; its normal associate is labradorite, and at the calcic end of the oversaturated rock series we find rocks consisting of plagioclase and augite or hypersthene, with only a trace of quartz and orthoclase left.

The soda-pyroxene, ægirine or acmite, makes its appearance only in the most alkaline varieties of granite, from which lime-felspar is almost or quite absent. Ægirine often exhibits a partial transformation into one of the blue soda-hornblendes; thus a crystal may have a core of ægirine and a mantle of riebeckite. These soda-rich minerals as a rule build spongy crystals which surround and incorporate quartz and felspar grains. Cases have

been observed in Finland and Scandinavia where an ordinary granite has been impregnated with ægirine by emanations from a younger soda-rich intrusion.

Tourmaline is only occasionally an important constituent of granitic rocks; like muscovite, it is practically confined to the more quartzose varieties, and it is rare in lavas. It crystallises at a late stage, and much of it is formed at the expense of earlier felspar and biotite. The usual variety is the black iron-tourmaline, which appears brown or blue in thin section; but pink, green, or colourless alkali-tourmaline is found in some pegmatite veins, often in association with lithia-mica. Tourmaline is never associated with hornblende or pyroxene.

Garnet is not an abundant mineral in granitic rocks, although individual occurrences are fairly numerous. It is found chiefly in aplite and pegmatite veins, and occasionally in acid lavas. The variety is almandine or spessartite, and the mineral is pink in hand specimen, but appears colourless in thin section.

Fayalite is a very rare constituent of these rocks. It has been found in a few cases only in drusy cavities in granite, in pegmatite veins, and in cavities in lava. In central Wisconsin, however, fayalite appears in quantity ranging from 1 to 5 per cent., as a normal constituent of certain hornblende granites and syenites (S. Weidmann). L. Hawkes has found fayalite in small quantity among the insets in an Icelandic lava, and A. Scott has recorded it in pitchstone in the island of Arran, Scotland.

Topaz, too, is largely confined to cavities and to pegmatite veins, where it is accompanied by muscovite, tourmaline, and sometimes cassiterite. In some rocks topaz replaces the felspar, and there have been produced in this way rocks that consist almost wholly of quartz and topaz.

Epidote is generally thought to be a secondary constituent, but C. R. Keyes has described well-formed crystals of this mineral in the granites of Maryland, and considers them to be primary constituents of the rocks. A. Laitakari has described epidote-granites in Finland.

The Chemistry of the Oversaturated rocks. A mixture of equal parts of orthoclase and albite has 67 per cent. of silica. Suppose a little quartz added to this, and some of the felspar to be replaced by mica (35 to 45 per cent. SiO_2), hornblende (about 50 per cent. SiO_2) or a pyroxene (55 to 60 per cent. SiO_2). It will readily be seen that unless a very large quantity of mica is

present, which is scarcely ever the case in nature, the percentage of silica in the mixture will hardly sink lower than 60 per cent.

A mixture of equal parts of albite and anorthite has 56 per cent. of silica. If this felspar is now mixed with a little quartz, and some augite (about 50 per cent. silica) or hypersthene (52-60 per cent. SiO_2) is added, the silica percentage of the mixture will again be about 60, but if a good deal of magnetite or ilmenite is present, it may bring the total silica down to a much lower figure.

Consulting H. S. Washington's tables of analyses of igneous rocks, the highest recorded percentage of silica in an unaltered eruptive rock (excluding quartz veins) is 84.1 in an aplitic rock from Nevada (Washington's Tables, p. 52). One of the lowest figures reached by this constituent is 44.9 in a " quartz-diorite gneiss " from Ontario (W. T., p. 528).

In an oversaturated rock consisting chiefly of orthoclase (18.5 per cent. Al_2O_3) albite (19.5 per cent. Al_2O_3) and muscovite (38 per cent. Al_2O_3) with biotite (averaging about 12 per cent. Al_2O_3), the total percentage of alumina should not depart far from 20 per cent., and it will at times exceed that figure. Tourmaline (about 34 per cent. Al_2O_3) and topaz ($55\frac{1}{2}$ per cent. Al_2O_3) will raise the alumina content greatly.

The addition of anorthite (37 per cent. Al_2O_3) would also tend to raise the proportion of alumina, were it not that when anorthite appears it is generally accompanied by hornblende, diopside, or hypersthene, for the most part non-aluminous, which at once depress it again. The addition of iron ore must reduce the alumina percentage still further. The lowest proportion of alumina is generally found in rocks that carry much ægirine, for in that mineral the place of alumina is taken by ferric oxide.

Washington records a granite from Siberia with 21.3 per cent. of Al_2O_3 (W. T., p. 166), and a felspathic rock from California (W. T., p. 300) in which no less than 25.5 per cent. of Al_2O_3 is said to be present, apparently along with a small quantity of quartz. The lowest recorded proportion of alumina is 5.1 per cent. in the riebeckite-rich granite of the island of Rockall (W. T., p. 586).

The content of lime rises from a mere trace, in rocks free from anorthite, to a proportion which, in theory at least, may approach 20 per cent. Pure anorthite has 20 per cent. of CaO, and diopside 26 per cent., thus a plagioclase-diopside rock with only a little quartz may well hold 15 per cent. of CaO. An

analysis of a quartz-diabase from Ontario records 12.7 per cent. of this oxide (W. T., p. 528).

Magnesia will be entirely absent if biotite, hornblende, and diopside are lacking. It reaches its greatest concentration in presence of much enstatite (MgO 40 per cent.) or diopside (18½ per cent. MgO). In a quartz-diorite from Mikonui, N.Z., J. S. Maclaurin found 12.3 per cent. MgO (W. T., p. 638).

With 12 per cent. of soda in albite, and 13.5 per cent. in ægirine, it should be possible to find an ægirine-granite with about 11 per cent. of soda. This figure is nearly reached by an ægirine-granite from Corsica, which holds 10.6 per cent. of Na_2O (W. T., p. 586). The theoretical minimum of no soda at all is also very nearly attained by a rhyolite from Borneo, which has only 0.03 per cent. of Na_2O to 10.01 per cent K_2O (W. T., p. 108).

Pure orthoclase carries 17 per cent. of potash, of which part is almost always replaced by soda. Muscovite has 12 per cent. of K_2O. In a quartz-porphyry from Thuringia the high figure of 12.3 per cent. of this oxide is recorded (W. T., p. 108). At the other extreme is a granite from Georgia, which has only 0.03 per cent. of K_2O, as compared to 6.31 per cent. of Na_2O (W. T., p. 244).

As regards iron oxides, a pure muscovite granite is practically free from these. If only silicates had to be considered, ferrous and ferric oxides would seldom be found to exceed seven or eight per cent. of the rock, but when magnetite or ilmenite is present the percentage may be very greatly increased (pure magnetite, 31 per cent. FeO, 69 per cent. Fe_2O_3). Among normal eruptive rocks, 14.14 per cent. of ferrous oxide is recorded in a quartz diabase from New Jersey (W. T., p. 606), and 13.23 per cent. of ferric oxide in the riebeckite-granite of Rockall (W. T., p. 586).

Oxides other than those mentioned above do not normally exceed a few tenths of one per cent., although in certain cases they may achieve an undue prominence. Thus 1.75 per cent. of P_2O_5 is reported in a quartz-diorite from Hesse (W. T., p. 390), and 5.04 per cent. of TiO_2 in a quartz-gabbro from New South Wales (W. T., p. 662). Zirconia, ZrO_2, forms 3.10 per cent. of an arfvedsonite-granite from Madagascar (W. T., p. 338); and manganous oxide, MnO, reaches 0.88 per cent. in a quartz-diorite from Colorado (W. T., p. 470). Boric acid is only found in tourmaline-bearing rocks; the greisen of St. Michael's Mount, Cornwall, carries 0.59 per cent. of B_2O_3 (W. T., p. 322). The same rock carries the high proportion of 3.36 per cent. of fluorine, as well

as 0.81 per cent. of lithia, Li_2O. Sulphur is often present in the form of one or the other of the sulphides of iron and copper; in a quartz-porphyry from Georgia, 1.14 per cent. of sulphur is reported (W. T., p. 340); while 0.83 per cent. of sulphuric anhydride, SO_3, was found in a quartz-diorite from Hesse, mentioned above. Carbonic acid is often present in the form of calcite, but it must be regarded as a decomposition product; and trivial quantities of chlorine and various heavy metals are often recorded.

The Sub-division of the oversaturated rocks. We have already discussed the primary sub-division of this class of rocks according to the ratio of orthoclase to anorthite. This method gives us, in the case of eucrystalline rocks, a group of *granites,* having Or>An, and a group of *tonalites,* with An>Or. The corresponding names for dyscrystalline rocks are *rhyolite* and *dacite.*

By the use of the orthoclase-albite ratio, we can now separate the *potash-granites* and the *potash-rhyolites,* in which Or>Ab, from the *soda-granites* and *soda-rhyolites,* which have Ab>Or; and also the *soda-tonalites* and *soda-dacites* (Ab>An) from the *lime-tonalites* and *lime-dacites* (An>Ab).

Among the very abundant soda-granites, there are some that hold a considerable proportion of plagioclase (oligoclase and andesine) in addition to orthoclase. For these rocks specific names have been coined by various workers, particularly granodiorite (Becker and Lindgren), adamellite (Cathrein), banatite (von Cotta), and quartz-monzonite (Brögger). The most widely used of these names is granodiorite, which stands for a granitic rock in which orthoclase and plagioclase are almost equally abundant. For a reason that we have already given, namely, the variable composition of the solid solutions that the microscopist calls " orthoclase " and " plagioclase," it is impossible to attach any chemical meaning to such a definition. Instead of the loosely named solid solutions, " orthoclase " and " plagioclase " we shall use the proportions of pure orthoclase (Or), pure albite (Ab) and pure anorthite (An) which are contained in these solid solutions, as a means of sub-dividing the group. If we examine the definition of granodiorite given at the beginning of this paragraph, remembering that " orthoclase " always contains more or less albite (an average of fifteen per cent. according to H. L. Alling) and that the plagioclase in these rocks

holds more albite than anorthite, then it appears that the ratio of Or : An in most granodiorites must have a value between 3 : 1 and 1 : 1. Here is a suitable basis for the definition of granodiorite, considered as a sub-division of soda-granite.

In the triangular diagram of *Fig.* 24, if we draw a line from the point Ab towards the point representing the composition Or_3An, on the opposite side of the triangle, this line will just

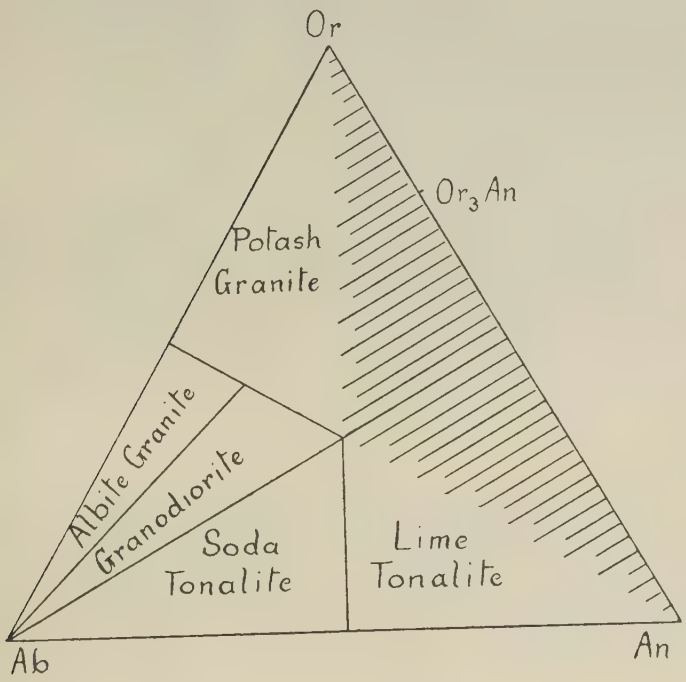

FIG. 26.

bisect the soda-granite field. In one half of the field there will now fall all soda-granites in which the ratio of Or to An exceeds 3 : 1; in the other half, those with orthoclase less than three times the anorthite. We may describe these as *albite-granites* and *granodiorites* respectively. The corresponding lavas will be *albite-rhyolite* and *rhyodacite*. (*Fig.* 26.)

In tabular form, then, we have the following classification of the oversaturated rocks :—

I. Eucrystalline Rocks.

- A. Granite (Or>An)
  - 1. Potash-granite (Or>Ab)
  - 2. Soda-granite (Ab>Or)
    - a. Albite-granite (Or>3 An)
    - b. Granodiorite (Or<3 An)
- B. Tonalite (An>Or)
  - 1. Soda-tonalite (Ab>An)
  - 2. Lime-tonalite (An>Ab)

II. Dyscrystalline Rocks.

- A. Rhyolite (Or>An)
  - 1. Potash-rhyolite (Or>Ab)
  - 2. Soda-rhyolite (Ab>Or)
    - a. Albite-rhyolite (Or>3 An)
    - b. Rhyodacite (Or<3 An)
- B. Dacite (An>Or)
  - 1. Soda-dacite (Ab>An)
  - 2. Lime-dacite (An>Ab)

Mesotype and melanocratic facies are so uncommon among oversaturated rocks that no special names have been given to them, and none will be proposed here. When necessary, one may speak of meso-granite, meso-granodiorite, etc.

REFERENCES.

Bayley, W. S.—U.S. Geol. Survey, Bull. 109, 1893.
Brögger, W. C.—Eruptivgesteine des Kristianiagebietes, vol. 2, *130*.
Daly, R. A.—(Distribution) Igneous rocks and their Origin, 1914, chap. 3.
do. —(Pigeon Point) Amer. Jour. Sci., 1917, *423*.
do. —(Purcell Mts.) Canada, Geol. Survey, Mem. 38, 1912, *221*.
do. — do. Festschrift H. Rosenbusch; Stuttgart, 1906.
Day, A. L.; Sosman, R. B.; Hostetter, J. C.—Amer. Jour. Sci., 1914, *33*.
Duparc, L. and Borloz, A.—Soc. Phys. Hist. Nat. Geneva, 1924, *13*.
Du Toit, A. L.—(Insizwa) Cape of Good Hope, Geol. Comm. 1910, *111*.

Emmons, W. H. and Larsen, E. S.—U.S. Geol. Survey, Bull. 718, 1923.
Goldschmidt, V. M.—Videnskaps Selskabets Skrifter, 1911.
Hawkes, L.—Quart. Jour. Geol. Soc., 1924, *549*.
Högbom, A. G.—Bull. Geol. Inst. Upsala, 1910.
Iddings, J. P.—U.S. Geol. Survey, Mon. 32, 1899.
Jaggar, T. A.—Amer. Geologist, 1898.
Joly, J.—Radioactivity and Geology, 1909.
do. —Nature, 1917, *456;* 1924, *160*.
Keyes, C. R.—U.S. Geol. Survey, 15 Ann. Rep., 1893.
Lacroix, A.—La Montagne Pelée et ses Eruptions, 1904.
do. —France, Carte Geol., Bull. 64, 1908; Bull. 71, 1900.
Laitakari, A.—Bull. Comm. Geol. Finlande, no. 51, 1918.
Lindgren, W.—U.S. Geol. Survey, 20 Ann. Rep., 1900.
Quensel, P. D.—Bull. Geol. Inst. Upsala, 1914, *129*.
Scott, A.—Trans. Geol. Soc. Glasgow, 1913, *68*.
Sederholm, J. J.—Bull. Geol. Comm. Finlande, no. 23, 1907.
do. —Intern. Geol. Congress, 1913.
Shand, S. J.—Trans. Edinburgh Geol. Soc., 1910, *376*.
Sollas, W. J.—Trans. Roy. Irish Acad., 1891, *427*.
Washington, H. S.—U.S. Geol. Survey, Prof. Paper 99, 1917.
Weidmann, S.—Jour. Geol. 1904, *551*.
Ussing, N. V.—Meddelelser om Grönland; Copenhagen, 1912.
Young, G. A.—Canada, Geol. Survey, Ann. Rep., 1906, part H.
Winge, K.—Geol. Fören. Förhandlingar, 1896, *187*.

CHAPTER IX.

THE OVERSATURATED ROCKS.

PART II. EXAMPLES.

A. Granites (including Granodiorites); Rhyolites (including Rhyodacites).

We define granite and rhyolite as those oversaturated rocks which contain more orthoclase than anorthite, granite being the name of the eucrystalline (well-crystallised) and rhyolite that of the dyscrystalline (ill-crystallised) varieties.

The great majority of granites, and all rhyolites, are leucocratic, with a colour index ranging from one to twenty-five. Many rhyolites show no dark minerals at all, except a few specks of iron ore, and some granites have as little as one per cent. of black or white mica. Such extreme cases have sometimes received special names, for example, "alaskite," but the condition can be expressed quite adequately by the use of a prefix. We shall employ the form leuco-granite or leuco-rhyolite when we wish to indicate that the rock in question holds less than, say, three per cent. of dark minerals. Well-known leuco-granites are the red granite of Ontario containing only 0.9 per cent. of biotite and 1.4 per cent. of magnetite (Adams and Barlow); the red granite of the Transvaal, in which P. A. Wagner records 0.5 per cent. of biotite, 0.75 per cent. of hornblende, and 0.7 per cent. of apatite and ore; and the acid granite of New South Wales, which carries only a trifling quantity of biotite and magnetite.

Mesotype granites (those with more than thirty per cent. of dark minerals) are distinctly uncommon, and in certain cases it can be demonstrated that they have arisen through the contamination of granitic magma by sedimentary material. Granites with a high colour index have been described by R. A. Daly in British Columbia. A variety occurring in the Purcell Range holds quartz 46, soda-orthoclase 29, oligoclase 2.5, and biotite 22 per cent.

In the granite of the Columbia Range, which normally carries only 10 per cent. of biotite and accessory minerals, there are black bands holding as much as 65 per cent. of biotite. These bands are considered to have been formed by the migration of certain oxides into zones of shearing in the granite.

The degree of acidity of granites and rhyolites is very variable, but the proportion of quartz (or tridymite) is most commonly between twenty and forty per cent. Granitic rocks have sometimes been described which hold as much as eighty per cent. of quartz, and special names (arizonite, northfieldite) have been given to them. These are just dyke-granites in the transitional stage between true eruptive rocks and quartz veins, and specific names are not needed for them; they are suitably described as peracid or even superacid granite. Any rock with more than, say, 45 per cent. of primary quartz is a peracid rock; while one in which quartz exceeds 60 per cent. deserves the adjective superacid. R. A. Daly has described peracid granites in the Purcell Mountains of British Columbia, in which the proportion of quartz reaches 57 per cent.

Granitic rocks with a rather low content of quartz are often called quartz-syenite. This is an unfortunate practice, for it has had the effect of obscuring the distinction between granite and syenite. Although syenite is by definition a rock containing little or no quartz, the name has actually been given to rocks carrying over twenty per cent. of the latter. Since the state of precise saturation with silica is rare, and syenites that really answer to the definition are uncommon, we may so far conform to custom as to extend the name of syenite to rocks that hold not more than ten per cent. of quartz; but those with more than ten and less than twenty per cent. of quartz should be described as subacid granite, and the corresponding lavas as subacid rhyolite.

Peraluminous Type.

This type is characterised by the presence of alumina in molecular excess of the sum of potash, soda, and lime. The excess goes typically into muscovite, but if enough magnesia is available, biotite may partly or wholly take the place of white mica, and in exceptional cases a lithia-mica is produced. Other peraluminous minerals are tourmaline, topaz, and certain kinds of garnet (almandine, spessartite).

The well known granites of Cornwall are muscovite-biotite granites with subordinate tourmaline and topaz. An admirable

quantitative examination of the St. Austell granite mass, carried out by W. A. Richardson, shows that the average composition of all varieties in that area is as follows :—

quartz	32.6	tourmaline	1.8
orthoclase	34.5	topaz	1.4
plagioclase	19.2	fluorspar	0.4
muscovite	4.5	magnetite	0.3
biotite }		apatite	0.3
lithia-mica }	4.7	cordierite	0.3
		Colour index	(13)

Within this single granite mass, which has an area of 32 square miles, the chief constituents show the following fluctuations :—

quartz, from ...	20 to 48	white micas, from	0 to 15
orthoclase, from	17 to 52	tourmaline, from	0 to 7½
plagioclase, from	9 to 31	topaz, from ...	0 to 7
dark micas, from	0 to 15	Colour index	(4 to 22)

It follows from the figures given for orthoclase and plagioclase that some part, even of this most typical of granites, is soda-granite. The published analyses of Cornish granites are about equally divided between potash and soda varieties, but a first-class analysis of the Land's End granite, by W. Pollard, shows 34 per cent. of normative orthoclase to 23 per cent. of normative albite.

One of the most highly potassic granites of Europe is the Stockholm granite, Sweden. This is a rather leucocratic granite in which biotite and some disseminated red iron oxide are the only dark minerals. Chemical analyses show about three times as much potash as soda, indicating that orthoclase is at least twice as abundant as albite. P. J. Holmquist states that no other Swedish granite is so rich in potash.

The biotite granite of Pike's Peak and Platte Canyon, Colorado, described by E. B. Mathews, is another distinctly potassic rock. The mineralogical composition is said to be as follows :—quartz 33, microcline 53, oligoclase 2.6, biotite and accessory minerals 10.7 per cent. The microcline contains, as usual, more or less soda, and so, although most analyses of Pike's Peak granite show Or in comfortable excess over Ab, there are some which show the latter molecule in excess.

The red granite or gneiss of Ontario is soda-granite of an extremely leucocratic character. The proportions of soda-orthoclase, microcline and oligoclase vary greatly from place to place.

A typical mode is given by Adams and Barlow as follows :—

quartz	37.7	anorthite	5.0
orthoclase	25.6	biotite	0.9
albite	29.3	magnetite	1.4
		Colour index	(2½)

Some of the " granodiorites " of the western states of America are peraluminous soda-granites. The table that follows gives the mineralogical composition of two such rocks from Idaho, described by W. Lindgren (1, 2); and one from the Sierra Nevada, according to H. W. Turner (3).

	1	2	3
quartz	29.2	28.0	33.0
orthoclase	18.1	15.8	20.7
albite	27.2	32.5	26.2
anorthite	9.5	11.1	12.9
biotite	12.3	7.5	5.6
ore	0.3	0.9	0.7
sphene and zircon ...	0.9	1.1	0.5
apatite, etc.	1.0	0.3	0.2
Colour index	(14)	(10)	(7)

A European soda-granite that has been very completely investigated is the beautiful porphyritic granodiorite of Shap Fell, Westmorland, which has insets of pink orthoclase in a pale gray groundmass. The composition has been worked out by A. Holmes, who finds that the insets make up just one-fifth of the rock, and that the total composition is quartz 24, " orthoclase " 36.2, oligoclase 33.6, biotite 5 8. Allowing for the albite that is held in solid solution in the orthoclase, the actual composition of the felspar is about Or 24, Ab 34, An 12.

Turning now to *rhyolite,* we find that potash-rhyolites in the Creede district of Colorado have been described by Emmons and Larsen. They are porphyritic rocks with occasional insets of orthoclase, soda-rich plagioclase, and biotite, in a crypto-crystalline groundmass composed of quartz and orthoclase. From a chemical analysis of the Willow Creek rhyolite, the composition is calculated to be as follows : quartz 35, orthoclase 53, albite 5, anorthite 0.3, with 5 to 7 per cent. of biotite. Soda-rhyolites as well as potash ones are developed in this district; one such rock, which Emmons and Larsen describe as " tridymite-latite," has the following composition : tridymite 20, orthoclase 29, albite 34,

anorthite 11.4, with 2 or 3 per cent. of biotite and a little apatite, magnetite and zircon. This is a rhyodacite.

A rock which Whitman Cross described as a mica-dacite, occurring in the Rosita Hills of Colorado, is a subacid soda-rhyolite. It has insets of biotite in a groundmass composed of orthoclase and plagioclase microlites, with a little quartz and tridymite. The calculated composition is quartz 18, orthoclase 26, albite 42, anorthite 8, biotite and ore 5.0 per cent. The same authority has described a soda-rhyolite at Chalk Mountain, Colorado, which is composed of large crystals of quartz, orthoclase, and oligoclase, with a few leaves of biotite, set in a comparatively scanty groundmass of the same composition; shrinkage cavities in this rock are lined with crystals of topaz, and an iron-manganese garnet is also a scanty constituent of the rock.

F. Bascom has described a garnet-bearing soda-rhyolite at Bay View, Maryland. Its composition is as follows:—

quartz	44.8	garnet	5.8
orthoclase	4.5	sphene	0.8
albite	30.6	magnetite	1.2
anorthite	2.8	rest	0.6
biotite	8.0	Colour index	(16)

The obsidians of the Yellowstone Park, well-known through the work of J. P. Iddings, are in part peraluminous soda-rhyolite. One of these lavas has the following normative composition:— quartz 37, orthoclase 22, albite 33, anorthite 4, together with 2.2 per cent. of corundum and a little hypersthene and iron ore. This rock would certainly have contained some five per cent. of mica if it had been able to crystallise.

Metaluminous Type.

Granites and rhyolites of this type contain one or other of the following mineral associations: biotite together with hornblende, augite (or primary epidote); hornblende together with augite (or epidote); hornblende alone (or epidote alone). Fayalite is occasionally present in small quantity, and in a soda-granite at Wausau, Wisconsin, it amounts to about 5 per cent. (S. Weidmann). The metaluminous type is much rarer among the potash than among the soda granites. An important example is the red granite of the Transvaal. P. A. Wagner gives the following mineralogical analysis of this rock:—

quartz	33.3	biotite	0.5
orthoclase	30.1	hornblende	0.75
albite	25.6	ore	0.3
anorthite	4.0	apatite, etc.	0.4
		Colour index	(2)

The gray granite of Ontario contains orthoclase, albite, and oligoclase in roughly equal amounts, with biotite, green hornblende, and frequently ortho- or clino-pyroxene as well (Adams and Barlow). The red granite of the same area carries a smaller proportion of dark minerals. An analysis of the red granite of Methuen township affords the following approximate estimation of the mineralogical composition : quartz 28, orthoclase 18, albite 42, anorthite 5, biotite, hornblende and ore (together) 7 per cent.

The most characteristic examples of granodiorite are metaluminous. The rock of the Boulder batholith, at Butte, Montana, is typical; it has been described by (1) W. H. Weed and (2) J. P. Iddings, and the two descriptions clearly refer to slightly different facies.

	(1)	(2)
quartz	23.7	22.5
orthoclase	19.9	17.6
albite	23.0	25.5
anorthite	11.5	17.0
biotite	4.2	9.8
hornblende	15.3	4.4
diopside	—	3.3
ore	1.2	0.7
sphene and apatite	1.3	0.1
Colour index	(22)	(18)

The next four examples are granodiorites from (1) Nevada City and (2) Grass Valley, California (W. Lindgren); (3) Haystack, Montana (W. H. Emmons); and (4) Bear Park, Montana (L. V. Pirsson).

	(1)	(2)	(3)	(4)
quartz	22	20.8	22.9	20.9
orthoclase	15	18	17.8	13.9
albite	29	28	30.7	36.6
anorthite	15	12.1	10.3	11.7
hornblende	16	16.6	9.7	6.2
biotite		—	4.2	7.7
ore	1.5	1.5	4.1	3.0
sphene	1.0	1.4	—	—
apatite	0.2	0.3	0.3	—
Colour index	(19)	(19)	(18)	(17)

Few European examples of this type of rock are available, simply on account of the general lack of quantitative data in the descriptions of most European granites. The granite of Mountsorrel, Leicestershire, probably falls to be included here, although the composition of the plagioclase is doubtful. W. A. Richardson gives the following statement of the mode of this rock : quartz 22.6, orthoclase 19.7, plagioclase 46.8, biotite 5.8, hornblende 3.9, ore 2.2 per cent.

The Orijärvi batholith, in Finland, is mainly granodiorite, according to the following mode which is furnished by P. Eskola :—

quartz	36.1	biotite	7.4
microcline	9.0	hornblende	4.7
albite	30.4	iron ores	1.7
anorthite	5.3	sphene, apatite	0.6
epidote	3.7	Colour index	(18)

As an example of albite-granite, we quote W. C. Brögger's statement of the composition of the granite of the Fen district, Norway :—

quartz	25.4	hornblende	3.4
orthoclase	23.3	sphene	0.5
oligoclase (Ab_6An_1)	40.4	magnetite	1.0
biotite	5.0	rest	0.6
		Colour index	(10)

The quartz-porphyry which is regarded as the ore-bringer of the great Kiruna magnetite deposits, in Lapland, is an albite-granite porphyry. As described by P. Geijer, it holds insets of microperthite and albite in a fine-grained reddish ground consisting of felspar, quartz, magnetite, a little pyroxene and a trace of biotite. Judging from chemical analyses, the composition must be roughly as follows :—

quartz	15 to 28	anorthite	1 to 4
orthoclase	12 to 26	pyroxene	1 to 3.5
albite	33 to 54	magnetite	3 to 8

Beautiful examples of metaluminous soda-rhyolite (rhyodacite) are described by H. H. Robinson, in the San Francisco district of Arizona. All degrees of crystallinity are represented among these lavas, but in most cases a cryptocrystalline to glassy base makes up about three-quarters of the rock. The insets are generally of plagioclase, with some of augite or hornblende, and rarely a few of quartz. It is interesting to compare the actual mineral composition of each rock with its " potential " composi-

tion, as calculated from chemical analysis; the comparison shows how misleading it is to name a hypocrystalline rock by the crystalline phases only.

		Kendrick Peak.	*San Francisco Mtn.*	*Mormon Mtn.*
Actual development	plagioclase	18.3	13.7	18.6
	biotite + hornblende	2.5	4.9	— / 8.1
	pyroxene	1.3	1.1	—
	ore	0.6	1.7	1.9
	groundmass	77.3	78.6	71.3
Potential composition if fully crystallised	quartz	24.6	20.0	22.0
	orthoclase	20.6	18.9	14.5
	albite	37.2	37.3	39.0
	anorthite	7.8	11.4	10.0
	biotite	2.0	2.5	—
	hornblende	1.0	2.5	8.0
	hypersthene	1.3	1.7	0.9
	ore	3.7	3.7	1.9
	apatite	0.3	0.3	0.3
	Colour index	(8)	(11)	(11)

Metaluminous soda-rhyolites in the Creede district of Colorado are described by Emmons and Larsen. These rocks have crystals of plagioclase, orthoclase, quartz, and biotite or hornblende, in a cryptocrystalline groundmass.

A glassy rhyolite occurring in the Yerington district of Nevada is described by A. Knopf. The black glass holds a few crystals of plagioclase (Ab_2An_1), biotite and sanidine, and some grains of pyroxene. Hornblende, magnetite and apatite are accessory. The norm shows quartz 21, orthoclase 26, albite 30, anorthite 12, and femic constituents 7.5 per cent.

An obsidian from Iceland, which was minutely studied by F. E. Wright and analysed by J. B. Ferguson, has the composition of a metaluminous rhyodacite. No minerals at all are developed in the rock, except a little fayalite and tridymite in shrinkage cavities, but the norm is as follows:—quartz 40, orthoclase 17, albite 27, anorthite 9, corundum 0.6, hypersthene 4.3 per cent. There is too little corundum to convert all the magnesia into biotite, so if the rock had crystallised it is most likely that an aluminous hornblende would have been formed.

Subaluminous Type.

Subaluminous granites are very uncommon, for although enstatite or diopside is fairly often present, as in the gray granites of Ontario, it is nearly always accompanied by more or less hornblende and biotite.

The granite described by C. F. Kolderup at Birkrem, Norway, sometimes called "birkremite" has the following mode:—quartz 24, orthoclase 20, albite 47, anorthite 6.7, hypersthene 1.6, ore 0.5 per cent.

The pre-Cambrian batholiths of Blue Ridge, Virginia, are composed of hypersthene granite, which has been called quartz-syenite in spite of the presence of 15 to 32 per cent. of normative quartz. The felspars are orthoclase and andesine (Ab_7An_3 to Ab_1An_1), and chemical analyses show sometimes Or, sometimes Ab in excess. Hypersthene, with a little augite and ore, make from 8 to 25 per cent. of the rock; hornblende is sometimes present too (Watson and Cline). The hypersthene granite or "charnockite" of St. Thomas' Mount, Madras, holds 40 per cent. of quartz, with 48 of microcline; 6 of plagioclase, 3 of hypersthene, 2 of iron ore and only a trace of biotite. The microcline is so rich in soda that Or and Ab are almost equal (H. S. Washington).

The subaluminous type is not uncommon among dyke-granites. The description, by A. Harker, of the granophyre of Carrock Fell, Cumberland, is applicable to many rocks of this kind. The approximate composition of the rock is as follows:—quartz 21, orthoclase 21, albite 43, anorthite 3.7, pyroxene 8.6 per cent. The groundmass of the rock shows every stage of gradation "from a coarse and irregular pegmatite to spherulitic intergrowths of a delicacy surpassing the resolving power of the microscope." Harker observes that granophyres (dyke-granites with graphic texture) generally carry pyroxene, and that in Carnarvonshire the typical granophyres have augite without biotite; the coarser granophyres and porphyries hold both augite and biotite; and the granites have biotite alone. Since very many rhyolites are subaluminous, it is likely that the series of rocks, from peraluminous granite through metaluminous porphyry to subaluminous rhyolite, bears witness to the effect of a progressive loss of fugitive constituents from the magma.

Subaluminous rhyolites are well represented in the Lipari Islands, and have been described by H. S. Washington. An example from Monte Guardia is a very fine-grained, ash-gray rock with small insets of pyroxene. The groundmass is micro-

crystalline, and is composed of minute laths of orthoclase, prisms of pyroxene, grains of magnetite, and interstitial quartz. According to Washington's analysis, the proportions of these minerals must be nearly as follows :—quartz 30, orthoclase 29, albite 34, anorthite 4, pyroxene 10, accessories 3. Other rhyolites of Lipari are completely glassy, but they may be recognised as potentially subaluminous types by the appearance of diopside and hypersthene in the norm, corundum being absent.

The " toscanites " of Tuscany, Italy, are mostly subaluminous rhyolites. These lavas have insets of orthoclase and labradorite, with augite, hypersthene, and some biotite, set in a glassy groundmass. The calculated composition of a rock from Monte Amiata is :—quartz 15, orthoclase 36, albite 25, anorthite 10, pyroxene 12, magnetite 1 per cent. (H. S. Washington).

The rhyolites of the Yellowstone Park are mostly subaluminous. They have been minutely described by J. P. Iddings. The insets are of quartz, orthoclase, plagioclase, and pale green augite or occasionally a little ortho-pyroxene. The groundmass varies from an almost structureless glass to globulitic and spherulitic types, and to cryptocrystalline and microcrystalline. It is mainly composed of orthoclase and quartz or tridymite.

Peralkaline Type.

Rocks of this type hold soda and potash in molecular excess over the available alumina; whenever this happens, the potash seems to exercise the stronger claim to combine with alumina, and it is always soda that is left in excess. Some of the superfluous soda may escape from the magma in solution, in the form of sodium carbonate, chloride, fluoride or silicate, but some is retained in soda-iron pyroxene, soda-iron amphibole, or in uncommon titanosilicates and zirconosilicates such as astrophyllite, eudialyte and ænigmatite. The commonest of these soda minerals is ægirine. Riebeckite and arfvedsonite are sometimes primary minerals, but in other instances they have been formed by the transformation of the original ægirine. In certain granites of Finland and Scandinavia, ægirine is said to have been introduced by solutions escaping from adjacent soda-rich magma.

Among the most characteristic rocks of this type are the riebeckite-ægirine granites of Quincy, Massachusetts, which have been described by C. H. Warren. A typical example of the Quincy granite gave quartz 33, sodipotassic felspar 55, and ægirine and riebeckite 10 per cent., with small quantities of

apatite, zircon, and astrophyllite. A darker variety from Copper Mine Hill yielded 7 per cent. of ægirine and 8.5 per cent. of riebeckite. The Quincy granite is cut by a younger meso-granite (the Squam River granite) which contains 40 per cent. of soda-hornblende (catophorite) and brown biotite, along with 35 per cent. of sodipotassic felspar and 25 per cent. of quartz (C. H. Clapp). So many beautiful varieties of peralkaline granite occur in Massachusetts, that this region, rather than the Christiania district, deserves to be the " type locality " for such rocks.

Even among such typically soda-rich rocks, potash felspar sometimes predominates over albite. A dyke-granite from the Kara River in Transbaikal, which was described by A. Karpinsky under the name of " karite," has the following composition :—

quartz	52.0	ægirine	20.1
orthoclase	20.5	pyrite	0.4
albite	6.7	iron oxide	0.2
		Colour index .....(21)	

The " grorudite " of W. C. Brögger is an ægirine-micro-granite which forms many dykes in the Christiania district of Norway. The composition of a typical example is as follows :— quartz 23, soda-potash felspar 53, ægirine and arfvedsonite 22 per cent. Similar rocks have now been recognised in many parts of the world. When instead of ægirine, riebeckite is developed, the names " paisanite " and " dahamite " have been used instead of grorudite; but so many names are not required for rocks which are all of one chemical type.

The " rockallite " of J. W. Judd is a mesotype soda-granite with 43 per cent. of ægirine, 26 per cent. of soda-potash felspar, and 30 per cent. of quartz. This curious rock was thought to form the entire islet of Rockall, in the North Atlantic, but Charcot has recently shown that rockallite only constitutes occasional dark patches (segregations) within a more leucocratic ægirine granite of which the islet is entirely composed.

As a general name for the peralkaline rhyolites, " pantellerite " may be used. This name was given by Förstner to lavas of Pantelleria, near Sicily, which have ægirine and ænigmatite as their characteristic dark minerals. The " comendite " of Sardinia is a similar rock in which a soda-amphibole takes the place of ægirine. These lavas show all the usual varieties of texture, but either ægirine or soda-amphibole may appear among the insets. The proportions of the essential

minerals in some of the lavas of Pantelleria are stated as follows, by H. S. Washington :—

	(1)	(2)	(3)	(4)	(5)
quartz	13	15	20	28	30
soda-microcline	70	63	63	45	51
soda-pyroxene	9	12	14	17	7
ænigmatite	6	10	3	10	12
magnetite	2	—	—	—	—
Colour index	(17)	(22)	(17)	(27)	(19)

In nos. 4 and 5, the felspar holds more orthoclase than albite.

Completely glassy lavas of this type may be recognised by the appearance of acmite or sodium metasilicate in the norm. For example, an obsidian from Yucatan, which was described and analysed by H. S. Washington, gives the following norm :—

quartz	35	sodium metasilicate	2.7
orthoclase	27	diopside	3.1
albite	24	hypersthene	0.2
anorthite	6.5	ilmenite	0.1

Had this magma crystallised, it must have given as its chief dark mineral a pyroxene intermediate between acmite and diopside, or more likely an amphibole of the corresponding composition. (Washington has observed that rocks which contain soda-amphiboles commonly have sodium metasilicate in the norm, while those with soda-pyroxene rarely show sodium metasilicate, and then only in small quantity.)

R. A. Daly describes a dark green obsidian which he found on Ascension Island. In the glass are minute needles of soda-diopside and some small insets of soda-orthoclase. The calculated composition of this rock is quartz 21, orthoclase 23, albite 44, soda-diopside 12 per cent.

B. Tonalites and Dacites.

This division includes all oversaturated rocks in which anorthite exceeds orthoclase. Plutonic rocks of this kind are often called " quartz-diorite," and some of them are included in the loosely defined varieties granodiorite and adamellite. Very often such rocks have simply been called " granite," although they may hold scarcely any monclinic felspar. The name tonalite was originally given by G. vom Rath to a hornblende-biotite-" granite " occurring at Tonale, in the Southern Alps, but its

significance has gradually become broadened, and we shall use it to embrace all eucrystalline rocks which satisfy the definition given above, regardless of the nature of the dark minerals. The corresponding lavas are the dacites, which take their name from the province of Dacia or Transylvania, in the loop of the Carpathian Mountains.

As a whole, the tonalites and dacites are appreciably less acid than the granites and rhyolites, although some tonalites have been described which hold over forty per cent. of quartz. They are also rather richer in dark minerals; and extremely leucocratic facies, such as frequently occur among granites, are unusual in this group. Mesotype and melanocratic facies are known, but like the corresponding facies of granite, they are probably due to contamination of the magma by solution of sediment. The dividing line between tonalite (with dacite) and diorite (with andesite) we shall draw, as before, at 10 per cent. of quartz, for the reason that the majority of rocks that have been described as diorite actually hold a little quartz.

By the application of the albite : anorthite ratio, we separate the soda-tonalites and soda-dacites from the lime-tonalites and lime-dacites. The latter type, in which anorthite exceeds albite, is scantily represented, the majority of tonalites and dacites being rich in soda. Peraluminous, metaluminous and subaluminous types all occur among tonalites and dacites, but the peralkaline type is unrepresented, because soda-pyroxenes and soda-amphiboles are incompatible with much anorthite.

Tonalite plays quite as large a part as granite in the composition of the great mountain ranges of the world. J. A. Bancroft states that " quartz-diorite " is the most prevalent eruptive rock in the Coast Range of British Columbia. A quantitative study of the average mineral composition of the rocks of the Coast Range in South-Eastern Alaska has been made by F. E. and C. W. Wright, with the following result :—

quartz	19.4	apatite	0.6
orthoclase	6.6	magnetite	0.9
andesine ($Ab_{56}An_{44}$)	47.4	pyrite	0.1
hornblende	7.6	sphene	1.3
biotite	11.6	decomposition products	4.5

It is clear, from these figures, that the average rock of the Coast Range is considerably more calcic than granite, and the bulk of it probably belongs to tonalite.

Tonalite is also a characteristic rock of the Alpine chain. The rocks of the Adamello Alps range from soda-granite to tonalite; so do those of the Riesenferner stock in the eastern Tyrol. The Brünner massif in Austria, and the "granites" of the Carpathians, include typical tonalites.

Peraluminous Type.

The composition of the tonalite of the Brünner massif, according to F. Sellner, and of two Carpathian tonalites described by P. Radziszewsky, are as follows:—

	Brünner massif	*Mitra, Carpathians*	*Wolfstal, Carpathians*
quartz	35	24	28
orthoclase	2.7	4.6	8.7
plagioclase	55	45	48
biotite	7.4	24	18
ore	—	0.2	—
zircon, apatite, etc.	0.3	2.4	0.4
Colour index	(8)	(26)	(18)

The peraluminous type of tonalite is also represented among the "granite-diorites" of Becker and Lindgren in Idaho; and F. L. Ransome's account of the Madera quartz-diorite, in the Globe district of Arizona, shows that this, too, is a true tonalite.

	Idaho	*Globe*
quartz	25.0	26.9
orthoclase	11.2	6.4
albite	30.2	23.2
anorthite	13.9	20.4
biotite	16.0	17.7
muscovite	—	1.0
ore	0.6	2.8
sphene, apatite, etc.	2.1	1.4
Colour index	(19)	(23)

J. H. L. Vogt has described dykes of lime-tonalite that cut the norite of Romsaas, Norway. They hold 15 per cent. of quartz, 75 of plagioclase of the mean composition $An_{55}Ab_{42}Or_3$, and 10 per cent. of biotite.

No description of a peraluminous dacite has been traced in the literature. Many rocks have been described under the name of mica-dacite, but they all fall into rhyolite in our system.

Metaluminous Type.

This is the commonest type of tonalite, just as it is the commonest type of soda-granite. It is well illustrated by the Marysville batholith, Montana, described by J. Barrell. Beside the latter we place two analyses of tonalites from the Haystack stock, in the same state; these are due to W. H. Emmons.

	Marysville	*Haystack*	*Haystack*
quartz	22.2	21.8	12.1
orthoclase	15.6	11.7	9.7
albite	26.3	30.1	31.2
anorthite	21.2	15.1	20.8
biotite	7.2	4.8	6.7
hornblende	5.5	—	—
pyroxene	—	11.2	13.5
ore	1.7	4.9	4.9
apatite, etc.	0.3	0.4	1.1
Colour index	(15)	(21)	(26)

The Electric Peak intrusion, in the Yellowstone National Park, is formed, according to J. P. Iddings, of a highly variable rock, which ranges from a leucocratic "quartz-diorite" to quite melanocratic rocks free from quartz. In most instances, pyroxene, hornblende and quartz are all present and are intergrown with one another; but Iddings makes the significant observation that with increasing coarseness of grain, hornblende becomes more abundant, and in the coarsest rocks of all, biotite predominates over hornblende, while pyroxene is entirely absent.

R. A. Daly describes great intrusions of tonalite in British Columbia. The examples quoted below refer to the Osoyoos batholith (1), the Remmel batholith (2), the Chilliwack batholith (3), and the Trail batholith (4).

	(1)	(2)	(3)	(4)
quartz	37.0	27.0	19.1	25.9
orthoclase	7.5	7.2	2.0	19.2
plagioclase (Ab>An)	33.1	50.7	55.7	28.1
biotite	10.8	5.7	10.3	13.4
hornblende	3.1	4.3	11.1	12.3
epidote	8.0	—	—	—
sphene	0.3	0.6	—	0.2
ore	—	3.8	1.3	0.6
apatite, zircon	0.2	0.7	0.5	0.3
Colour index	(22)	(15)	(23)	(27)

The Bayonne batholith is composed of a mesotype tonalite, for which Daly gives the following statement :—

quartz	19.5	augite	4.4
orthoclase and perthite	21.1	sphene	0.6
plagioclase	23.8	magnetite	0.9
biotite	16.2	epidote, apatite	1.7
hornblende	11.8	Colour index	(35)

Melanocratic types containing 40 to 50 per cent. of hornblende occur in the Purcell Mts. (Daly).

It is interesting to note that such a typical " continental " rock as tonalite has been found by W. G. Foye in the Fiji Islands. The mode of this rock is quartz 20, plagioclase 73, biotite 1.3, hornblende 2.8, and ore 2 per cent. (Colour index 6.)

A hornblende dacite is described by J. S. Diller, at Mount Shasta, California. It is a light gray rock, with a few insets of hornblende. The groundmass is sometimes holocrystalline, but more often it holds some brown glass; it is composed of plagioclase with hornblende and some little grains of hypersthene and magnetite. The mode is not stated, but the norm shows quartz 20, orthoclase 7, albite 37, anorthite 25, dark constituents 10 per cent.

The " porphyrite " of Mt. Hilliers, one of the laccolitic hills of the Henry Mts. in Utah, is apparently a dacite. It has insets of plagioclase and hornblende, in a groundmass of orthoclase and quartz. The yellow-green hornblende shows signs of resorption, with production of augite. The norm contains quartz 15, orthoclase 13, albite 38, anorthite 20, and dark constituents 12 per cent.

Dacites and quartz andesites have been described by H. I. Jensen, and also by H. C. Richards, in the Glass House Mountains and elsewhere in Queensland. The Glass House dacite is microcrystalline, with insets of plagioclase and quartz in a groundmass which contains augite, a little hornblende, and magnetite. Jensen's analysis affords the following norm :—quartz 16.6, orthoclase 16.7, albite 30.4, anorthite 19.7, dark constituents 15 per cent.

In many cases where the name dacite has been used, but no mineralogical analysis is given, it is impossible to determine whether the rocks so described belong to dacite, as here defined, or to rhyolite or andesite.

Subaluminous Type.

Few examples of subaluminous tonalite have been traced in petrographical literature; no doubt they are rare, just as subaluminous granites are. On the other hand, subaluminous dacites may be expected to occur very frequently, but it is hard to detect them in the literature, since they have generally been called " andesite " and very few andesites have been described in quantitative mineralogical terms.

The " hypersthene-quartz-diorite " of the Shevaroy Hills in Madras, one of the intermediate members of T. H. Holland's " charnockite series " is a subaluminous tonalite. The mode of this rock has been determined by H. S. Washington; it is quartz 15.5, felspar (mainly andesine) 55.5, hypersthene 23.6, ore 5.4 per cent. (Colour index 29.)

J. S. Diller has described as " hypersthene andesite " a lava on the west slope of Mount Shasta, California, which appears to be a lime-dacite. It is a light gray, compact rock, with a few insets of hypersthene. The mineralogical composition is not stated quantitatively, but the norm shows 16 per cent. of quartz, 8 of orthoclase, 26 of albite, 39 of anorthite, and 11 of dark minerals.

The " hypersthene andesites " of Crater Lake, Oregon, carry a basic plagioclase, with hypersthene, augite and magnetite, in a hypocrystalline to glassy base. The norms, calculated from five chemical analyses which accompany H. B. Patton's description of these rocks, show from 10.7 to 15.5 per cent. of quartz, so these rocks are probably subacid dacites.

Some of the " andesites " of the Sierra Nevada, which are described by H. W. Turner, are probably dacites. A " pyroxene andesite " from Plumas County, for example, has 17.5 per cent. of quartz in its norm.

Dacites accompanied the eruption of Souffrière, St. Vincent, in 1902. According to J. S. Flett, these lavas have insets of zoned plagioclase, augite and hypersthene, in a groundmass of felspar, quartz, tridymite, hypersthene and glass. Analyses of the lavas and their ashes show from 10 to 15 per cent. of quartz, with anorthite in large excess over orthoclase.

Some remarkable rocks of basaltic appearance, from the Firth of Clyde, Scotland, have been described by G. W. Tyrrell under the name of " cumbraite." One of these rocks exhibited 58 per cent. of crystals in a glassy base, this proportion being made up of anorthite 7, labradorite 31, enstatite and augite 20 per cent.

The composition of the glass that forms the remaining 42 per cent. of the rock is such that if it had crystallised it must have formed quartz (about 35 per cent.), orthoclase (about 35 per cent.), and albite (about 30 per cent.). Combining these figures with those given first, it appears that if the cumbraite had crystallised completely it would have had nearly the following composition :— quartz 14.7, orthoclase 14.7, albite 28.8, anorthite 21.8, pyroxene 20, with a trace of magnetite. The rock consequently falls into soda-dacite.

REFERENCES.

Adams, F. D. and Barlow, A. E.—Canada, Geol. Survey, Mem. 6, 1910.
Bancroft, J. A.—Canada, Geol. Survey, Mem. 23, *83*.
Barrell, J.—U.S. Geol. Survey, Prof. Paper 57, 1907.
Bascom, F.—Maryland Geol. Survey, 1902.
Brögger, W. C.—Eruptivgesteine Kristianiagebietes, I., *6*.
Charcot—see Lacroix, Comptes Rendus, 1921, *267*.
Cross, W.—(Chalk Mtn.) U.S. Geol. Survey, Bull. 20, 1885, *21*.
do. —(Rosita Hills) U.S. Geol. Survey, 17 Ann. Rep., 1896.
Daly, R. A.—(Brit. Columbia) Canada, Geol. Survey, Mem. 38, 1912.
do. —(Ascension) Proc. Amer. Acad. Arts Sci., 1925, *61*.
Diller, J. S.—U.S. Geol. Survey, Educ. Bull. 150, *222*.
Emmons, W. H.—Jour. Geol., 1908, *212*.
do. and Larsen, E. S.—U.S. Geol. Survey, Bull. 718, 1923.
Eskola, P.—(Orijärvi) Comm. Geol. Finlande, Bull. 40, 1914.
Flett, J. S.—Phil. Trans. Roy. Soc., 1903, *353*
Förstner, H.—Italy, Boll. Com. Geol., 1881, *550*.
Foye, W. G.—Proc. Amer. Acad. Arts Sci., 1918, *1*.
Geijer, P.—Geology of the Kiruna District, (2) Stockholm, 1910.
Gilbert, G. K.—Geology of the Henry Mts., Washington, 1877.
Grout, F. F.—Jour. Geol., 1925, *467*.
Hackmann, V.—Finland, Comm. Geol., Bull. 72, 1925.
Harker, A.—(Carrock Fell) Quart. Jour. Geol. Soc., 1895, *125*.
Holmes, A.—(Shap Fell) Petrographic Methods, 1921, *394*.
Holmquist, P. J.—Bull. Geol. Inst. Upsala, 1906, *77*.
Iddings, J. P.—(Yellowstone) U.S. Geol. Survey, Mon. 32, 1899.
do. —(Electric Peak) U.S. Geol. Survey, 12 Ann. Rep., 1891, *569*.
do. —(Butte) Igneous Rocks, vol. I., *447*.
Jensen, H. I.—Proc. Linn. Soc. New South Wales, 1906, *169*.
Judd, J. W.—Trans. Roy. Irish Acad., 1897, *48*.
Karpinsky, A.—Russia, Kaiserl. Min. Gesellschaft, 1904, *65*.
Knopf, A.—U.S. Geol. Survey, Prof. Paper 114, 1918.
Lindgren, W.—(Idaho) U.S. Geol. Survey, 20 Ann. Rep., 1900.
do. —(Nevada) U.S. Geol. Survey, 17 Ann. Rep., 1897.
do. —(Clifton) U.S. Geol. Survey, Prof. Paper 43, 1905.
do. and Loughlin, G. F.—U.S. Geol. Survey, Prof. Paper 107, 1919.

Mathews, E. B.—Jour. Geol., 1900; U.S.G.S., Bull. 148, 1897.
Pirsson, L. V.—(Montana) U.S. Geol. Survey, 20 Ann. Rep., 1900.
Pollard, W.—Gt. Britain, Mem. Geol. Survey (Land's End), 1907.
Radziszewsky, P.—Poland, Service Geol., 1924, *97*.
Richardson, W. A.—Quart. Jour. Geol. Soc., 1923, *546*.
do. —(Mountsorrel) ditto, *554*.
Robinson, H. H.—U.S. Geol. Survey, Prof. Paper 76, 1913.
Sellner, F.—Tschermak's Min. Pet. Mitt., 1922, *141*.
Smith, G. O. and Calkins, F. C.—U.S. Geol. Survey, Bull. 235, 1904.
Turner, H. W.—U.S. Geol. Survey, 14 Ann. Rep., 1893.
Tyrrell, G. W.—Geol. Mag., 1917, *305*.
Ussing, N. V.—Meddelelser om Grönland; Copenhagen, 1912.
Vogt, J. H. L.—Norsk Geologisk Tidskrift, 1918, *229*.
Wagner, P. A.—S.A. Geol. Survey, Mem. 20, 1922, *35*.
Warren, C. H.—Proc. Amer. Acad. Arts Sci., 1913, *203*.
Washington, H. S.—(Charnockite) Amer. Jour. Sci., 1916, *323*.
do. —(Lipari) Amer. Jour. Sci., 1920, *446*.
do. —(Pantelleria) Jour. Geol., 1913, *653, 683;* 1914, *16*
do. —(Toscanite) Jour. Geol., 1897, *37*.
do. —(Yucatan) Jour. Wash. Acad. Sci., 1921, *484*.
Watson, T. L. and Cline, J. H.—Bull. Geol. Soc., Amer., 1916, *193*
Weed, W H.—Jour. Geol., 1899, *739*.
Weidmann, S.—Jour. Geol., 1904, *551*.
Wright, F. E.—Bull. Geol. Soc. Amer., 1915, *259*.
do. and C. W.—U.S. Geol. Survey, Bull. 259, 1905.

CHAPTER X.

THE SATURATED AND TRANSITIONAL ROCKS.

PART I. GENERAL.

A SATURATED rock is one which contains neither free silica nor any unsaturated mineral such as nepheline or olivine. If this criterion were strictly applied, the class would be a very limited one, for many of the rocks that have been described as syenite, monzonite, or diorite, and that are regarded as typical examples of their kind, actually hold as much as ten per cent., and sometimes more, of quartz; and many gabbros, dolerites, and basalts have either a little interstitial quartz or a good deal of olivine.

A small quantity of an unsaturated mineral is easy to recognise, for olivine stands out in high relief in thin sections, and felspathoids can be discovered by staining; but quartz, on account of its similarity to felspar, and its very late crystallisation in the majority of rocks, may be present to the extent of several units per cent. without being detected under the microscope. In a hypocrystalline rock, any excess of silica tends to be retained in the glassy base, so it cannot be detected unless a chemical analysis is made, and even when a complete analysis is available, the calculation of the mineralogical composition of the rock presents difficulties. The " norm " employed in the American system of classification is no safe guide in the matter, for in consequence of the method followed in computing the norm, quartz may appear on paper although it is entirely absent from the rock.

For these reasons it is impossible to apply the saturation criterion with absolute strictness, as regards the presence or absence of quartz. *Along with the really saturated rocks, then, we shall discuss those transitional varieties in which the amount of free quartz or tridymite lies between zero and ten per cent.* But as regards the lower boundary of the group, there can be no concession to a careless custom. The state of exact saturation with silica marks a phase-boundary in the system, at which one characteristic phase has just disappeared and another is just about to appear; the presence of the smallest recognisable quantity of

any unsaturated mineral such as nepheline or olivine indicates the crossing of the boundary, and justifies, or even demands, a change in the name of the rock.

The geology of the saturated rocks. Since saturation with silica is an intermediate stage between oversaturation and undersaturation, saturated rocks ought to be relatively rare. This anticipation is realised, for although individual occurrences of such rocks are numerous enough, they seldom reach the dimensions of even a small granite batholith. The largest bodies of saturated rock are probably the " anorthosite " intrusions of eastern Canada, which occupy altogether about 60,000 square miles of the surface of Quebec and Labrador. To the Saguenay mass alone an area of 5,800 square miles is conceded by F. D. Adams, and to the Morin mass nearly 1,000 square miles. The main anorthosite body in the Adirondack Mountains of New York covers nearly 1,200 square miles. The huge norite intrusion of the Bushveld, Transvaal, spreads itself over more than 12,000 square miles; the Duluth gabbro of Minnesota occupies at least 2,400 square miles; and the area of the Sudbury norite sheet in Ontario is not less than 500 square miles. It must be stated that none of these great intrusions consists wholly of a single rock type, and that within these areas, both oversaturated and undersaturated varieties are often present.

Although their extent is so considerable, it has been definitely established that many of these intrusions have the form of sheets or laccolites, not that of batholiths, which means that the volume of rock is much less than that contained in a batholith of the same diameter. The Bushveld norite and the Sudbury norite are thick sheets, with a probable thickness of more than three miles in the first case and less than two miles in the second. The Duluth gabbro is regarded as a laccolite by Van Hise and Leith, who calculate that the maximum thickness is about 20,000 feet. Even the Canadian anorthosites are considered by R. A. Daly to be laccolitic in form, and N. L. Bowen views the Adirondack anorthosite as a sheet-like body. The numerous masses of norite in the charnockite series of India are stated by T. H. Holland to have the form of lenses and thick dykes.

Another point that must be taken into consideration, in any attempt to estimate the volume occupied by saturated rocks, is that large intrusions are seldom of uniform composition throughout. A condition that is commonly recognised in sheets and

laccolites is that the higher levels carry quartz and the lower levels olivine; but it is seldom possible to indicate these facies on a geological map or to make any accurate estimate of the volume of each facies.

The anorthosites present some very puzzling problems. This name is given to rocks which consist almost wholly of plagioclase felspar, generally labradorite but sometimes bytownite. According to F. D. Adams, quartz is probably never present as a primary constituent of these rocks. Every known body of anorthosite seems to be associated with ordinary gabbro or norite, and there is a complete and uninterrupted transition from the former into the latter. But it is remarkable that, while gabbro and norite are freely intruded in the form of dykes among other rocks, and are represented among effusive rocks by the abundant basalts and andesites, dykes of anorthosite are rare, and lavas of such composition are almost unknown.

N. H. Winchell, studying the Duluth gabbro and the associated anorthosite, came to the conclusion that plagioclase crystals had floated upwards in the dense gabbro magma, and had accumulated near the roof of the intrusion, forming anorthosite. R. A. Daly has also taken this view of the matter, without, however, going so far as N. L. Bowen, who contends that no such thing as an anorthosite *magma* ever did or could exist, and that all anorthosite *rocks* must have been formed by the separation of plagioclase crystals from a gabbroic magma. Bowen conceives that in such a magma the heavy phases, such as pyroxene, will first sink to the bottom of the magma-chamber, forming a basal sheet of pyroxenite, and that when the residual magma is sufficiently lightened by this process the plagioclase crystals will also sink and give rise to masses of anorthosite, leaving the last portion of the magma of syenitic or granitic composition. Bowen has applied this view to the anorthosites of the Adirondack Mountains; but it is opposed by W. J. Miller, who holds that the anorthosites of that region were formed by the sinking of pyroxene crystals out of gabbroic magma, leaving behind a viscous, but still fluid, residue of anorthositic magma.

Each of these views represents anorthosite as a derivative of gabbro or norite magma, and any of them can be applied successfully to the smaller sheets and lenses of anorthosite which occur in alternation with layers of norite and pyroxenite in complex intrusive bodies like the Bushveld and the Duluth gabbro, where the anorthosite is a minor member of the entire body; but

whether any such explanation will suffice to explain the genesis of the great Canadian and American anorthosite bodies is another question, for in these the gabbro-norite seems to form an altogether subordinate element in the complex; so much so that the Adirondack anorthosite as a whole has been described as consisting of "little else than felspar."

This remarkably interesting problem is only to be solved by detailed field work, and it is to be hoped that it will receive the attention that it deserves from all who have the opportunity of studying anorthosites in the field. It should be noticed that the gravitational theory is not the only possible explanation of the problem of the anorthosites, for Adams and Barlow describe an occurrence of anorthosite among metamorphic limestones in the townships of Harcourt, Dudley and Bruton, Ontario, and remark that the stratigraphical relations are such as to "make it almost impossible to consider it as other than an alteration product of the limestone."

Coming now to saturated rocks with a larger proportion of dark minerals, which are at present covered by the names syenite, monzonite, diorite and gabbro, with trachyte, latite, andesite and basalt for the corresponding lavas, we find that these names are actually applied to many oversaturated and undersaturated rocks as well as to strictly saturated ones. So far as we make use of these names, we shall restrict their meaning in accordance with the principles which we have already laid down, confining them to rocks which hold no unsaturated minerals whatever and not more than ten per cent. of quartz or tridymite.

The *syenites* are either marginal modifications of great bodies of granite, or else they rise, in the form of dykes, stocks, or cupolas, from the roof of a granite batholith. Thus the Plauen and Meissen syenites of Saxony are local phases of the Meissen granite; the Beverley syenite is a facies of the Quincy granite in Massachusetts; the granite of Upsala, Sweden, passes locally into syenite; the syenite of Bulawayo occupies an outlying lobe of the Matopo granite in Southern Rhodesia; and the Palabora syenite of the eastern Transvaal bears the same relation to the Palabora granite. In some instances, however, syenite forms a marginal facies about a foyaite intrusion; this is the case at Umptek, in the Kola Peninsula; while at Ahvenvaara in Finland, as well as in the much better known districts of Haliburton and Bancroft in Ontario, syenite occupies an intermediate position between granite and foyaite, and is transitional into both. The syenites of the

central Transvaal, and those of the Monteregian Hills in Quebec, occupy distinct stocks, pipes and dykes of small dimensions. Special problems connected with the origin of the syenites will be discussed, along with those relating to the undersaturated alkaline rocks, in a later chapter.

The names *diorite* and *monzonite* have been used so loosely that it is difficult to establish any generalisations about rocks so named. Some so-called diorites hold thirty or forty per cent. of quartz and from two to four times as much orthoclase as plagioclase; these are no diorites at all, but granodiorites and tonalites. Of the rocks that have been called monzonite, some are syenites, some granites and some tonalites. Monzonite was originally a collective name used by de Lapparent for all the plagioclase-bearing rocks found at Predazzo and Monzoni, and one cannot expect a geographical name to have a precise mineralogical significance. It is certain that monzonites and diorites, according to any strict mineralogical definition, are much less common than one would gather from the frequency with which these names are used in geological publications, and it is likely that they are all transitional rocks, associated on one hand with granites and tonalites and on the other hand with gabbros and norites.

Gabbro and *norite* are found in enormous intrusive bodies, almost comparable with the great granite intrusions. The norite sheet of the Transvaal, with an area of some 12,000 square miles, is one of the greatest intrusions in the world, even if its thickness does not exceed the figure of 20,000 feet which A. L. Hall allots to it. The Sudbury norite and the Duluth gabbro are comparable in area with many granite masses; and the quantity of matter contained in the dolerite sheets which bulk so largely in the Karroo formation of South Africa, and in formations of similar age in India, Tasmania, and South America, would be enough to make several batholiths. There is consequently no reason to assume that gabbro and norite are derivatives of anything else, in the sense that syenite and monzonite are derivatives of granite. Indeed, it is frequently assumed, as we saw in Chapter VIII., that granite itself is a derivative of gabbroic (basaltic) magma.

The *perknites* are dark-coloured, heavy rocks formed entirely of pyroxenes, amphiboles and ores, sometimes with garnets in addition. Perknites usually occur in the form of sheets and lenses within larger bodies of syenite, diorite or gabbro, or they may constitute marginal modifications of these rocks; but the mass of the perknite facies is never more than a very small frac-

tion of that of the rocks with which it is associated, and completely independent intrusions of perknite are uncommon. In keeping with this, there are no lavas of perknitic composition. The formation of perknites has been ascribed to the sinking of the first-formed crystals in a large body of magma, and their accumulation near the floor of the reservoir. The first crystals to be formed are generally iron ores and pyroxenes, and one may accept the theory of gravitational settling of crystals as a likely explanation of the origin of many bodies of pyroxenite at least. For the more hornblendic rocks some modification of the theory may be necessary, for the crystallisation of hornblende often takes place after that of plagioclase. In some cases, such as that of the rock called " davainite " by B. K. N. Wyllie and A. Scott, occurring at Garabal Hill, Scotland, it has been possible to prove that the hornblende was formed by transformation of pyroxene, and that the original rock was a pyroxenite.

A special problem is presented by rocks which consist almost entirely of oxides of iron and titanium. Among the gabbros and norites in many parts of the world there are dyke-like and sheet-like bodies of nearly pure iron ore, which behave as if they were independent intrusions. C. F. Kolderup has described an ilmenite-rock at Ekersund, Norway; W. Petersson, magnetite-spinel rocks in Sweden; A. L. Hall, thick sheets of titaniferous magnetite in the Transvaal; and Watson and Taber, dykes of ilmenite, rutile and apatite in Virginia. The difficulty about regarding these as eruptive rocks is that the melting points of magnetite, ilmenite, and spinel lie far above the range of temperature to which normal eruptive rocks bear witness. Further investigation of the genesis of these remarkable ore-bodies is called for. When the ores are sufficiently diluted with silicates, the difficulty disappears on account of the mutual lowering of freezing points, so it is not necessary to question the eruptive nature of the magnetite-syenites of Kiruna, Sweden, or the still more remarkable syenite with 63 per cent. of magnetite, which A. Lacroix reports in Madagascar. That such rocks may be truly eruptive is shown by the discovery in Colorado, of blocks of lava which hold more than 50 per cent. of iron ore (Washington and Larsen).

The mineralogy of the saturated rocks. The minerals of the saturated rocks are the same that occur in the oversaturated group, with the exception that quartz and tridymite are typically absent. Along with the excess of silica, muscovite, lithia-mica,

tourmaline and topaz virtually disappear as primary constituents, although a certain amount of white mica may be produced by the bleaching of biotite and by the alteration of felspar.

The felspars differ in no way from those of the last group. Pure orthoclase and pure albite remain uncommon, but the intergrowths which we call perthite and microperthite, and the various solid solutions which are described as soda-orthoclase, anorthoclase and soda-microcline are found in all the more alkaline rocks. The plagioclase series of solid solutions occurs in its entire range from practically pure albite to practically pure anorthite, with a small percentage of the orthoclase molecule present in addition. In all known cases, the alkali-rich felspars crystallise later than the lime-rich ones, and a zonal structure is frequently produced in consequence of the earlier crystals acquiring mantles of successively more and more alkaline composition, ending with albite or soda-orthoclase.

The dark minerals of the saturated rocks are biotite and all the chief varieties of amphibole and pyroxene. Among the amphiboles, the green ferrous hornblende is commonest; the brown, ferric and aluminous varieties are less usual; while the soda-iron amphiboles are confined to the soda-syenites and soda-trachytes, and are remarkable for their very late crystallisation. While the hornblende in the more siliceous members of this division is apparently primary, that in the more calcic rocks has often been formed by the transformation of earlier pyroxene crystals. The so-called " uralite " is a pseudomorphic hornblende, which retains the external form of the augite crystals which it has replaced. Sometimes the pyroxene crystals have mantles of hornblende around them; in other cases relics of pyroxene are still to be seen at the heart of large hornblende crystals; and it sometimes happens that the ophitic texture or the diallagic structure of augite has been preserved, although the material itself has been completely replaced by bunches of hornblende needles.

Pyroxene occurs in many varieties. Ortho-pyroxene (enstatite or hypersthene) has a great development in the norites and andesites, and clino-pyroxene (diallage or augite) in the gabbros, dolerites and basalts. The lime-rich pyroxenes, diopside and hedenbergite, are chiefly found in syenites; and ægirine and soda-diopside are still less common.

Fayalite is known to occur in a very few syenites; and in some cases where " olivine " is recorded in a syenite or trachyte without further details, it is likely that the mineral is fayalite.

Epidote is a common product of the alteration of felspar or hornblende, and it has been claimed as a primary constituent in a few instances. Sphene is usually present in small quantity, and other titanosilicates and zirconosilicates often containing rare earths have been obtained from syenites and syenite pegmatites.

Of minerals other than silicates, magnetite and ilmenite are the most important, and apatite is a common accessory constituent. In the more melanocratic rocks, sulphides of iron, copper and nickel, such as pyrite, bornite, chalcocite, pentlandite and pyrrhotite, are developed in lenses and pockets, and in some cases these must be regarded as original constituents of the magma.

The chemistry of the saturated rocks. Since albite is the most highly siliceous mineral proper to the saturated rocks, it is clear that no strictly saturated rock can have more than 69 per cent. of silica, and that very few of them will even approach that figure. A few rocks have been described by the name of "albitite," but they do not consist of pure albite. An albitite from the Ural Mountains, described by Duparc and Pearce, holds 89.3 per cent. of the albite molecule and shows 67 per cent. of silica; and a "soda-syenite" from Tuolumne County, California, has 95 per cent. of albite and 67.5 per cent. of silca. It is true that many rocks with more than 69 per cent. of silica have been called syenite, but all such rocks, as well as many others with less silica, contain appreciable or even large amounts of quartz. Thus a so-called "syenite-porphyry" from St. Barthelemy, West Indies, has over 30 per cent. of normative quartz, although the silica percentage is only 66 (Washington Tables, p. 261). A "syenite" from Clifton, Utah, has 67 per cent. of silica and 22 per cent. of normative quartz (W. T., p. 183); and a "syenite" from Neudeck, Silesia, with only 60 per cent. of silica, has 21 per cent. of normative quartz (W. T., p. 365). Such rocks cannot be called syenite without destroying any chemical significance that can be attached to the name.

Among syenites proper, which are practically free from quartz, the silica percentage lies most commonly between 55 and 63. With increasing lime in the felspar, silica decreases, and in the anorthosites, which consist almost wholly of lime-rich plagioclase, the silica content ranges from 45 to 53 per cent. An increase in the proportion of dark silicates in the rock will not necessarily reduce the silica any further, because the pyroxenes themselves

have from 45 to as much as 60 per cent. of silica; consequently most gabbros, norites and pyroxenites hold 45 to 55 per cent. of silica. If the latter figure is exceeded, in a labradorite-bearing rock, some quartz is almost sure to be present. But if the rock contains much magnetite, ilmenite or chromite, the silica percentage will be greatly reduced; thus the " ostraite " or spinel-pyroxenite of the Ural Mountains has only 34 per cent of silica (W. T., p. 669).

Alumina varies generally between 14 and 18 per cent. in the syenites, but it increases rapidly with increasing lime-felspar, and reaches its highest value in the anorthosites. The anorthosite of Nain, Labrador, has 28 per cent. of alumina (W. T., p. 303); and in an anorthosite from New Caledonia, over 33 per cent. of alumina is recorded, corresponding to about 85 per cent. of anorthite (W. T., p. 305).

Among the perknites, on the other hand, alumina sinks very low. The hornblende-hypersthene rock of Pallavaram, Madras, has only 5.4 per cent. of Al_2O_3; an enstatite rock from Marico, Transvaal, has 2.1 per cent. of Al_2O_3; and one from Santa Clara, California, has 1.7 per cent. of Al_2O_3 (W. T., p. 703).

As regards lime, this oxide rises to 20 per cent. in anorthite and 26 per cent. in diopside, so it should stand highest in anorthosites and perknites. In the anorthosite of New Caledonia, mentioned above, lime amounts to 17.7 per cent., and many gabbros have from 10 to 13 per cent. of CaO. E. S. Larsen reports a pyroxenite unusually rich in sphene, which gives 24.7 per cent. of CaO (W. T., p. 721); Duparc and Pamfil record pyroxenites in the Ural Mountains which hold 22-23 per cent. of CaO (W. T., p. 735); and a very melanocratic gabbro from Burnt Head, Maine, shows nearly 21 per cent. of CaO. In some syenites and trachytes, on the other hand, lime falls to less than 1 per cent.

High magnesia goes with high lime in many gabbros and norites. Thus a norite at Cow Bridge, Wyoming, has CaO 10.49, MgO 12.87 (W. T., p. 645); another from Cecil Co., Maryland, has CaO 11.42, MgO 10.05 (W. T., p. 667). In a pyroxenite from the Ural Mountains L. Duparc records 14.8 per cent. of CaO and 12.5 per cent. of MgO (W. T., p. 669); but more usually the pyroxenites are richer in one of these constituents than in the other. Thus a bronzite rock from New Caledonia shows 30 per cent. of MgO to 2.5 per cent. of CaO (A. Lacroix); an enstatite rock from Transvaal has 29.3 per

cent. of MgO to 1.7 per cent. of CaO (W. T., p. 735); a hypersthene rock from Norseman, W. Australia, has MgO 28.3, CaO 2.9 (W. T., p. 703). Pure enstatite holds 40 per cent. of MgO.

Soda reaches its maximum in highly albitic rocks like the soda-syenite porphyry of Tuolumne Co., California, with 11.5 per cent. of Na_2O to only 0.1 per cent. of K_2O (W. T., p. 285), and the albitite of Koswinsky-Kamen, Ural Mountains, with 10.8 per cent. of Na_2O to 0.5 per cent. of K_2O (W. T., p. 285). Pure albite holds 11.8 per cent. of Na_2O.

Potash should approach 17 per cent. in a pure orthoclase rock. An " orthoclasite " found by C. W. Wright in Alaska gave 12.4 per cent. of K_2O, a value which does not seem to have been exceeded anywhere in a saturated rock. Among ordinary syenites, K_2O runs from about 5 to 8 per cent., and Na_2O has a similar range.

Titania rises to a very high value in some gabbros and norites which are rich in ilmenite. Over 18 per cent. of this oxide is recorded in an ilmenite-norite from Soggendal, Norway, which also holds 25 per cent. of FeO (W. T., p. 727). Rocks consisting of nearly pure ilmenite have been described in Norway and Virginia, but for reasons already stated these can not be regarded as eruptive rocks in the usual sense. From 1 to 3 per cent. of TiO_2 is commonly present in ordinary gabbros and norites, and in a sphene-rich pyroxenite from Colorado, E. S. Larsen has found over 5 per cent. of TiO_2. " Kragerite " and " nelsonite " are rocks that carry much rutile, but their eruptive origin is perhaps questionable.

A. Lacroix describes a magnetite-syenite from Andavakoera, Madagascar, consisting of magnetite (63 per cent.) and orthoclase, with a little muscovite. If this is an unaltered eruptive rock, it is unique in holding over 52 per cent. of ferric oxide. That such rocks may nevertheless be eruptive is suggested by the occurrence of a magnetite basalt in Colorado, which contains 56 per cent. of iron ores, together with bytownite, augite, and apatite (Washington and Larsen).

The sub-division of the group of saturated (and transitional) rocks. Following the lines which we have already laid down, we first separate the rocks in which orthoclase exceeds anorthite from those in which the reverse is the case. For the groups so established, the names *syenite* and *diorite* will be used,

with *trachyte* and *andesite* for the dyscrystalline varieties; but these names will apply to the leucocratic facies only. In order to distinguish the strictly saturated rocks from the transitional varieties which contain more or less quartz, one may use the prefix *ortho-*, as in ortho-syenite.

The orthoclase-albite ratio subdivides the syenites further into potash-syenite and soda-syenite; and the albite-anorthite ratio separates soda-diorite from lime-diorite. Trachytes and andesites are split up in the same way as syenite and diorite respectively.

It is customary to recognise an intermediate group of rocks between syenite and diorite, to which the name " monzonite " is given. This is defined by W. C. Brögger as a rock in which orthoclase and plagioclase are nearly equal; it should therefore have the composition of a granodiorite *minus* quartz. But the quantitative examination of the typical monzonite of the Tyrol shows it to have a colour index of about 35. F. Becke has given a more precise definition of monzonite; he states that the ratio of Or : Ab : An in typical monzonite is about 35 : 45 : 20, and that the dark and light constituents are approximately equal in quantity. Hence, according to Becke as well as Brögger, the typical monzonite is a mesotype rock. To give this name to leucocratic rocks in our system would be to change its meaning in an essential respect. It happens, however, that leucocratic rocks of similar composition to monzonite are well-known; Brögger first described them in Norway, giving them the name of *akerite* and defining them as rocks intermediate in composition between syenite and monzonite.

We may therefore subdivide the group of soda-syenites, just as we did the soda-granites, into

soda-syenite, group A (having Or : An$>$3 : 1) and
soda-syenite, group B (having Or : An$<$3 : 1$>$1 : 1).

To the second group, the name akerite is appropriate, with monzonite for the mesotype and melanocratic facies. The corresponding lavas will be called trachyandesite and trachybasalt respectively. It is doubtful whether there are any lavas of the latter kind at all.

For the mesotype and melanocratic facies of potash-syenite and soda-syenite (group A), L. V. Pirsson's name " shonkinite " may be used. Lavas of this composition are unknown.

For the very abundant mesotype and melanocratic rocks in which anorthite exceeds orthoclase, we shall use the name *gabbro*. In the past, gabbro has been distinguished from diorite either by the more calcic nature of its plagioclase or alternatively by the presence of pyroxene instead of amphibole; but neither method has been applied consistently, and we shall reject both, and distinguish gabbro from diorite by the colour ratio alone. In making this departure from the customary procedure, we have the support of no less an authority than Joseph Barrell, who maintained that " any granular rock composed to a considerable degree of dark minerals, even if largely or completely hornblende, should be classed with the gabbros and not with the diorites."

The lavas corresponding to gabbro are universally known as *basalt*. By means of the albite-anorthite ratio we distinguish between *soda-gabbro* and *lime-gabbro, soda-basalt* and *lime-basalt*.

Lastly, we have among the saturated rocks a group characterised by the virtual absence of all light minerals; for these the group name of *perknite*, introduced by H. W. Turner, is suitable.

In the absence of a mineralogical analysis of a saturated rock, the norm calculated from the chemical analysis is not always a reliable guide to the orthoclase-albite-anorthite ratio, for a certain quantity of lime and alumina that belong to other minerals are generally calculated as anorthite in the norm, hence the normative anorthite may largely exceed the amount actually present in the rock. An illustration of the difference between the norm of a rock and its mode is given by a shonkinite from Celebes, which Iddings and Morley have described. This rock is said to be composed of " much augite and biotite, with subordinate orthoclase," yet the norm shows 13 per cent. of anorthite, with 6 per cent. of nepheline in place of albite.

Peraluminous, metaluminous, subaluminous and peralkaline types are all represented among the syenites, the shonkinites and the trachytes; but the peralkaline type does not occur in diorite, andesite, gabbro or basalt. With increasing lime content, the peraluminous type becomes very uncommon.

The subdivisions of the saturated rocks may be shown conveniently in tabular form, as follows (compare the classification of the oversaturated rocks, page 152):—

I. Eucrystalline Rocks.

Leucocratic.	*Mesotype and Melanocratic.*
Potash-syenite.	Potash-shonkinite.
Soda-syenite { group A (albite-syenite). group B (akerite).	Soda-shonkinite { group A group B (monzonite).
Soda-diorite.	Soda-gabbro.
Lime-diorite.	Lime-gabbro.

II. Dyscrystalline Rocks.

Potash-trachyte.	(unknown).
Soda-trachyte { group A (albite trachyte).	(unknown).
group B (trachyandesite).	Trachybasalt.
Soda-andesite.	Soda-basalt.
Lime-andesite.	Lime-basalt.

REFERENCES.

Adams, F. D.—Canada, Geol. Survey, Guide Book 3, 1913.
do. and Barlow, A. E.—Canada, Geol. Survey, Mem. 6, 1910, *94*.
Barrell, J.—U.S. Geol. Survey, Prof. Paper, 57, 1907, *46*.
Becke, F.—Festschrift C. Doelter, Dresden, 1920.
Bowen, N. L.—Jour. Geol., 1917, *209*.
Brögger, W. C.—(Akerite) Zeit. Kryst., 1890, *43*.
do. —(Monzonite) Eruptivgesteine Kristiania, II., 1895, *6*.
Daly, R. A.—Igneous Rocks and their Origin. *241*.
De Lapparent, A.—Annales des Mines, 1864, *259*.
Duparc, L. and Pamfil, A.—Bull. soc. min. France, 1910, *369*.
Hall, A. L.—(Norite) Jour. Chem. Min. Met. Soc. S. Africa, 1926, *165*.
do. —(Magnetite) S. Africa, Geol. Survey, Ann. Rep., 1909, *70*.
Holland, T. H.—India, Geol. Survey, Mem. 28, 1900, *134*.
Iddings, J. P. and Morley, E. W.—Jour. Geol., 1915, *231*.
Kolderup, C. F.—Bergens Museums Aarbog, 1896.
Lacroix, A.—Mineralogie de Madagascar, II., *379, 387*.
Larsen, E. S.—Cited in Washington's Tables, *721*.
Miller, W. J.—Bull. Geol. Soc. Amer., 1918, *399*.
Peterssen, W.—Geol. Fören. Förhandlingar, 1893, *49*.
Turner, H. W.—Jour. Geol., 1901, *507*.
Van Hise, C. R. and Leith, C. K.—U.S. Geol. Survey, Mon. 52, 1911, *372*.
Washington, H. S. and Larsen, E. S.—Jour. Wash. Acad. Sci., 1913, *449*.
Watson, T. L. and Taber, S.—U.S. Geol. Survey, Bull. 430, 1910.
Winchell, N. H.—Geol. Nat. Hist. Survey of Minnesota, Bull. 22, 1893.
Wyllie, B. K. N. and Scott, A.—Geol. Mag., 1913, *499, 536*.

CHAPTER XI.

THE SATURATED AND TRANSITIONAL ROCKS.

PART II. EXAMPLES.

A. Syenites and Trachytes (including Akerites and Trachyandesites).

Syenitic rocks in which the dark minerals are so reduced in quantity as to be nearly negligible, and which may consequently be described as leuco-syenite, are known, but they are not common nor do they form masses of large size. Some of the syenites of Quebec are highly leucocratic, that of Shefford Mountain holding sometimes less than one per cent. of mica or hornblende, according to Sir W. Logan. When the felspar crystals are large, and the dark minerals more or less concealed in their interstices, it is easy to under-estimate the importance of the latter and to form the impression that the rock consists " almost entirely " of felspar, when it may really hold five or ten per cent. of dark minerals. For example, a rock from the Ural Mountains, which Duparc and Pamfil described as " albitite," carries enough lime, iron and magnesia to form at least five per cent. of dark minerals; and an " orthoclasite " from Alaska, described by C. W. Wright, must hold quite ten per cent. of dark minerals, judging from its chemical composition. J. Phemister has given the name of " perthosite " to certain syenites in the north-west of Scotland, which consists almost entirely of perthitic felspar, with only 1 to 3 per cent. of dark minerals. In a typical case, the dark minerals were diopside 1.75, magnetite 0.5, sphene 0.25 per cent., leaving 97.5 per cent. of felspar.

Peraluminous Type.

The syenites of Durbach and Meissen, Germany, are always quoted as examples of mica-syenite. The Durbach syenite is a marginal facies of the Black Forest granite; in part it is a pure mica syenite, but the biotite is very often accompanied by hornblende. Quartz is generally present, and no doubt a good deal of rock that would be better described as subacid granite has been included under the name of syenite. The biotite syenite of Meissen, Saxony, is also quartz-bearing, and it is doubtful whether there is any true syenite in the area at all.

Syenitic facies occur among the granites of Ontario. Adams and Barlow describe a soda-syenite that consists of red microperthite with three or four per cent. of biotite, and a little muscovite, calcite, and apatite. Another soda-syenite, from Craigmont, has about 85 per cent. of felspar, 13 of titanomagnetite, and a little biotite. A red syenite at Monmouth has the following composition :—

quartz	4.2	
orthoclase ...	37.2	forming microperthite, 84.5
albite	45.6	
anorthite ...	1.7	
muscovite ...	4.8	
biotite	3.9	
apatite	0.7	
calcite	1.6	

Colour index (9).

Some of the " hedrumite " of Norway is peraluminous soda-syenite. The hedrumite of Ostö has the following composition, according to W. C. Brögger :—

alkali-felspar	83	(Or 26, Ab 54, An 3)
biotite (lepidomelane)...	13.5	
apatite	0.5	
magnetite, sphene, etc.	0.5	
calcite	2.5	

Colour index (15).

Potash-syenites are much less common than soda-syenites. A. Lacroix describes a highly potassic syenite-aplite in Madagascar, consisting of microcline and albite, with muscovite, biotite, and a very little quartz. The calculated norm shows 63 per cent. of Or, 18 of Ab, and 6 of An.

Many rocks have been described under the name of mica-trachyte, but most of them are either so quartzose that they are properly rhyolites, or else they carry metasilicates in addition to biotite and therefore belong to the metaluminous type. The trachyte of Game Ridge, in the Rosita Hills of Colorado, seems to be a true peraluminous trachyte. According to W. Cross, it shows insets of sanidine, plagioclase and biotite in a groundmass of orthoclase and oligoclase, with a little quartz.

Metaluminous Type.

The hornblende syenite of the Plauenscher Grund, Dresden, has long been regarded as the typical example of this kind of rock; yet a good deal of the rock that passes for syenite, and is found in rock collections all over the world, holds 10 per cent. or more of quartz. A mineralogical analysis of the Plauen syenite, by H. S. Washington, gave the following result:—

quartz	10	magnetite	2
soda orthoclase	65	sphene	2
oligoclase	3	apatite	1
hornblende	17	Colour index	(22)

The available chemical analyses of this rock show from 5 to 7 per cent. of normative quartz. Whether any part of the Plauen mass is free from quartz does not appear in the descriptions, but Rosenbusch mentions the absence of quartz from the syenite at Kisselbusch, which is another peripheral facies of the Meissen granite.

The " nordmarkite " of the Christiania district of Norway is a very leucocratic syenite passing into subacid granite. The dark minerals are generally brown biotite and green hornblende, and a little acid plagioclase is present; but peralkaline rocks have been described under the same name.

Metaluminous orthosyenites have been described at various points in Quebec and Ontario. At Port Coldwell, Ontario, H. L. Kerr mentions a red syenite consisting of microperthite, deep brown hornblende (which sometimes shows cores of pyroxene), a little biotite, sphene, and apatite, and a few grains of quartz. The syenite of Brome Mountain, Quebec, described by J. A. Dresser, holds 90 per cent. of felspar (cryptoperthite, Or 30, Ab 55, An 5) along with 10 per cent. of biotite, pyroxene, hornblende, sphene and apatite. The same geologist has described the syenite of Shefford Mountain, Quebec, which consists of microperthite with very little pale green augite, green hornblende and brown biotite, as well as traces of sphene and occasionally a few grains of quartz.

Beautiful examples of soda-syenite have been described by L. V. Pirsson in Montana. The syenite of Highwood Peak has pale green diopside and brown biotite as its chief dark minerals, but some green hornblende has been formed by transformation of diopside, and there is a good deal of white mica present which is a bleached form of biotite. The syenite of Yogo Peak is very

similar to the last. Pirsson states the composition of these two syenites as follows:—

	Highwood Peak	*Yogo Peak*
quartz	8.2	6.1
orthoclase	24.5	27.5
albite	46.7	37.5
anorthite	—	7.5
mica	12.0	—
hornblende	—	12.9
diopside	7.7	5.4
ore	1.1	3.1
Colour index	(21)	(21)

Syenites in New Hampshire have been described by L. V. Pirsson and H. S. Washington. The syenites of Tripyramid Mountain and Belknap Mountain have the composition stated below. Beside them is placed the mode of the Coryell syenite, British Columbia, according to R. A. Daly.

	Tripyramid Mountain	*Belknap Mountain*	*Coryell*
quartz	1	4.2	5.1
soda-potash felspar	80	68	51.2
plagioclase	6.5	2.5	17.9
biotite	1	7.6	—
hornblende	6	13.4	20.2
augite	1	—	1.5
ore	4	3.8	1.7
apatite, etc.	0.5	0.5	2.2
Colour index	(12)	(25)	(26)

The soda-syenites of the Aker type take their name (akerite) from a locality in the Christiania district of Norway, but the published descriptions of Norwegian akerites are most inadequate. Biotite is the chief dark mineral, but diopside or hypersthene is always present too, and fibrous green hornblende results from transformation of pyroxene. In the akerite of Ramnäs, the ratio of Or : Ab : An in the norm is 18 : 46 : 18, and the femic constituents make up about 15 per cent. of the norm.

A typical akerite occurs in the Leeuwfontein stock, Transvaal. It consists of about 80 per cent. of felspar, which has cores of plagioclase and mantles of anorthoclase, together with brown hornblende (about 12 per cent.) diopside, biotite, ore and accessories.

Very similar rocks occur in the Monteregian Hills of Quebec. The akerite of Shefford Mountain, described by J. A. Dresser, carries plagioclase, soda-orthoclase, pyroxene, biotite, and brown hornblende. The akerite of Mount Yamaska is described as follows, by G. A. Young :—

quartz	7.9	diopside	0.8
orthoclase	16.7	ore	6.0
albite	43.0	apatite	2.2
anorthite	9.2	accessories	1.4
biotite	11.8	Colour index	(21)

The same type occurs in Tripyramid Mountain, New Hampshire (L. V. Pirsson) and at Cuttingsville, Vermont (J. W. Egglestone). Each of these rocks carries about 80 per cent. of felspar, consisting partly of soda-orthoclase and partly of oligoclase or andesine, together with brown hornblende and either diopside or biotite, besides the usual accessory minerals.

The majority of trachytes are metaluminous. The widely known rocks of the Drachenfels and other hills in the Siebengebirge of the Rhine are porphyritic rocks with large insets of soda-orthoclase in a pale gray, microcrystalline to hypocrystalline base. Some plagioclase is always present, and among the scanty dark minerals biotite and hornblende are commonest, though diopside is sometimes present too. The hornblende crystals often have a corroded appearance, and are changed externally into grains of pyroxene and ore; this is just the reverse of the transformation usually observed in syenites. The glass base is highly siliceous, and a little quartz is sometimes recognisable in the groundmass. The norm of the Scheerkopf trachyte is quartz 6.4, orthoclase 47.8, albite 28.8, anorthite 7.8, leaving about 10 per cent. of metasilicates, mica and accessories.

The trachytes of Monte Gibelé, Pantelleria, are porphyritic rocks holding soda-microcline, colourless pyroxene (but sometimes sodic pyroxene, and then passing over to the peralkaline type), and a little brown hornblende. A trace of quartz may be present in the interstices. H. S. Washington gives the composition of one of these lavas as follows :—

quartz	3	hornblende	5
soda-microcline	83	magnetite	2
pyroxene	7	Colour index	(14)

Metaluminous trachytes from Bolsena and Vetralla, Italy, are also described by Washington, who states that in these rocks

" both olivine and quartz are wanting or only present sporadically." The following modes are given :—

orthoclase	49.5	44.3	48
albite	21.7	27.0	27
anorthite	14.4	14.1	12
diopside	6.4	3.2	7.4
biotite	3.4	4.8	1.0
accessory	4.6	6.6	4.1
Colour index	(14)	(14)	(12)

A perfect example of an almost precisely saturated *trachy-andesite* is found in the Leeuwfontein complex, Pretoria; it is the effusive form of the magma which furnished the akerite described above (page 189). It is a dark-gray rock of andesitic appearance, with some insets of plagioclase. Under the microscope each plagioclase crystal is seen to be zonally built, with a core of oligoclase-andesine and a broad mantle of anorthoclase in which tiny grains of dark minerals are embedded. The groundmass is composed of unstriated felspar and greenish hornblende, gray diopside, and green to brown biotite, with titanomagnetite and apatite. The dark minerals are often clustered together, a grain of diopside being surrounded by hornblende, biotite and ore grains which seem to have resulted from transformation of the pyroxene. The composition of the rock is approximately as follows (S. J. S.) :—

anorthoclase (about $Ab_7An\ Or_2$)	65 to 70 per cent. by volume.
plagioclase (about $Ab_3\ An$)	12 to 15
hornblende	12
diopside	2.5
biotite	2
titanomagnetite	2.5
apatite	1
Colour index	(20)

H. S. Washington describes as " latite, Monfina type " a trachy-andesite from Italy. This is a porphyritic rock with insets of biotite and augite, and some of felspar, in a microcrystalline to cryptocrystalline groundmass. The mode is

quartz	6.8	biotite	7.3
alkali-felspar (Or_2 Ab)	33.3	ores	6.0
plagioclase (Ab_2An_3)	34.1	apatite	0.4
augite	12.1	Colour index	(26)

The rock of Mount Pennell, in the Henry Mountains of Utah, is a trachyandesite, according to the data furnished by Whitman Cross, and so are some of the " andesites " of the Rosita Hills, Colorado. The dark minerals are augite, biotite and hornblende, and the felspars have cores of plagioclase with mantles of soda-orthoclase. In the mantles, tiny grains of the dark minerals are enclosed, just as in the rock of Leeuwfontein, Transvaal.

L. V. Pirsson has described a trachyandesite in the Highwood Mountains of Montana. It carries orthoclase, labradorite, hornblende, a little biotite, and a residue of glass. Felspars and glass make up 83 per cent. of the rock, and hornblende 15 per cent. The glass is so siliceous that the norm shows 10 per cent. of quartz.

Subaluminous Type.

Subaluminous syenites seem to be distinctly uncommon, for although diopside is one of the commonest constituents of syenites, it is either accompanied by hornblende or mica, which take the rock into the metaluminous class, or else it holds acmite in solid solution, and the rock is then peralkaline.

Subaluminous trachytes ought not to be too uncommon, but well-described examples of this type are not numerous. Good examples have been described by H. S. Washington on the island of Sardinia. The Cuglieri type is porphyritic, with large felspar crystals and a few black augites in a light-gray, microcrystalline groundmass. The felspar is chiefly soda-orthoclase, but some acid plagioclase appears too. No quartz is visible in this rock. The mode is as follows :—quartz 2, soda-orthoclase (Or_7Ab_3) 62, andesine (Ab_3An) 26, augite 5, ores 5 per cent.

The Sennariolo type is dense and very fine grained, almost without insets of any kind, and is composed of very small laths of alkali felspar and a few grains of pale gray augite and magnetite, in a colourless, glassy base. The mode in this case can only be calculated from the chemical analysis : it is approximately quartz 2.5, soda-orthoclase 73, andesine 16, augite 3.5, ores 5 per cent.

The trachyte of Monte Arci has insets of soda-microcline in a dense gray base which is composed of felspar and quartz with a few grains of augite and magnetite. The mode is quartz 8, soda-microcline 83, pyroxene 6, ores 3 per cent.

Peralkaline Type.

This type is widely represented, for the pyroxene in most examples of syenite tends to hold a little of the acmite molecule, or to be mantled by soda-diopside or soda-hornblende. The felspar is always a purely alkaline variety, either soda-orthoclase, soda-microcline, albite, or some variety of microperthite.

The syenite of Umptek, Kola peninsula, Finland, is a very leucocratic rock composed of microperthite, arfvedsonite and ægirine; according to W. Ramsay and V. Hackmann, it forms the border facies of a nepheline syenite. A very similar rock, which is also associated with nepheline rocks, has been described by P. D. Quensel at Almunge, Sweden; this rock contains two soda-amphiboles, a brown arfvedsonite and a blue green hastingsite.

Peralkaline syenites are well developed in Norway. The rock to which W. C. Brögger has given the name "lestiwarite" is a leucocratic orthosyenite with 91 per cent. of felspar (cryptoperthite), $7\frac{1}{2}$ per cent. of ægirine, and $1\frac{1}{2}$ per cent. of sphene. The "sölvsbergite" of the same writer is a dyke syenite with parallel texture. Two typical analyses of sölvsbergite give the following results:—

quartz	4.5	0.7
potash felspar	29.5	30.0
soda-felspar	50.5	51.0
soda-diopside	15.5	—
soda-hornblende	—	14.7
ægirine	—	2.5
zircon, etc.	—	1.0

Brögger's "hedrumite" also consists in part of peralkaline syenite, but rocks of several types have been included under that name.

The peralkaline granites of Massachusetts pass locally into syenite. The Beverley syenite is virtually free from quartz; the dark minerals are sometimes ægirine and sometimes soda-hornblende, with accessory biotite, magnetite and sphene (C. H. Clapp). F. E. Wright has observed that the hornblende crystals sometimes exhibit cores of diopside. An analysis of the Beverley syenite, by F. E. Wright, shows that the rock must consist of about 38 per cent. of orthoclase and the same quantity of albite, with some 20 per cent. of metasilicates and a little quartz and ore. The rock of Wigwam Quarry, according to Clapp, has 70

per cent. of alkaline felspar, 8 per cent. of quartz, and 22 per cent. of riebeckite and ægirine.

A beautiful peralkaline orthosyenite is developed near Bulawayo, S. Rhodesia, where it forms a lobe of the Matopo Hills granite (F. P. Mennell). Both pale-green diopside and dark-green soda-hornblende are present, along with microperthite and sphene. Quartz is entirely absent.

A. L. Hall describes a pyroxene-syenite at Palabora, in the Eastern Transvaal, which consists of pink or white felspar and a bright green pyroxene; the latter transforms locally into blue arfvedsonite, so it must be a soda-pyroxene (soda-diopside to soda-hedenbergite). This rock is adjacent to a large body of limestone, and with closer approach to the limestone the pyroxene increases in amount until it largely exceeds the felspar, and the rock becomes shonkinite and eventually pyroxenite.

Syenites with blue amphiboles and biotite have been described by A. Lacroix in Madagascar. Among them there is a potash syenite or pegmatite consisting solely of microcline and an unusual variety of soda-amphibole (torendrikite); this rock is exceptionally rich in potash, containing 11.2 per cent. of K_2O to 2.8 per cent. of Na_2O.

Peralkaline trachytes are well developed in eastern Australia and New Zealand, where they have been described by H. I. Jensen, H. C. Richards, and P. Marshall. The trachytes of the Nandewar Mountains carry both ægirine and a deep blue hornblende, with about 90 per cent. of felspar (sanidine and anorthoclase) and sometimes a little interstitial quartz. Ægirine trachytes occur on Mount Flinders; Jensen gives the composition of one of them thus: anorthoclase 75 per cent., ægirine 20, magnetite 5. A similar rock in the Canobolas Mountains has 80 per cent. of felspar, 15 of soda-diopside, and 5 of accessories. Arfvedsonite and brown hornblende are the principal dark minerals in trachytes of the Warrumbungle Mountains; and arfvedsonite and riebeckite in those of the Glass House Mountains. One of the latter holds 85 per cent. of felspar, 10 to 14 of riebeckite and other soda-amphiboles, a little ægirine, and accessory magnetite and zircon.

Similar rocks are found in New Zealand. P. Marshall describes trachytes with sanidine or anorthoclase and a little soda-diopside and magnetite, as well as one or two per cent. of quartz, near Dunedin.

A. Holmes has described a trachyte of Mozambique, East

Africa, which contains 77 per cent. by weight of anorthoclase, 13 per cent. of soda-amphiboles (cossyrite, catophorite, arfvedsonite), 8 per cent. of ægirine and soda-diopside, and a little ore and zircon.

B. Shonkinites and Monzonites.

The name shonkinite, derived from Shonkin Sag in the Highwood Mountains of Montana, was introduced by Weed and Pirsson to describe a rock consisting of nearly equal volumes of augite and orthoclase. Some of the rocks that were included in shonkinite were slightly undersaturated, a little olivine being generally present, and sometimes nepheline or sodalite. The same name has since been given to rocks holding quite a considerable proportion of nepheline or olivine, so that it has almost lost its original meaning. Another name, malignite, was introduced almost at the same time as shonkinite, and used by A. C. Lawson to describe the mesotype syenites and nepheline syenites of Rainy River, Ontario. We shall employ shonkinite as a general name for all mesotype and melanocratic syenites which contain no unsaturated minerals, reserving malignite for the undersaturated alkaline rocks. The name monzonite has already been defined.

No peraluminous monzonite or shonkinite seems to have been described in quantitative terms. Many of the dyke-rocks which pass under the name "minette" are of this type.

Metaluminous Type.

Mesotype and melanocratic syenites (shonkinites) are developed in connection with the Vermilion granite batholith of Minnesota, and have been described by F. F. Grout. One of these rocks has the following composition:—

quartz	5	hornblende	30
orthoclase	20	biotite	3
oligoclase	40	accessories	2
		Colour index	(35)

Another shonkinite in the same area has about 50 per cent. of hornblende, and another still has 80 per cent. of hornblende, 5 of biotite, and some felspar, magnetite and apatite.

Numerous examples of shonkinite have been described in British Columbia. The following figures refer to (1) shonkinite

of Franklin mining camp (C. W. Drysdale); (2) shonkinite of Rossland (R. A. Daly).

	(1)	(2)
quartz	—	0.5
soda-orthoclase	56	13.4
plagioclase	—	7.2
biotite	—	8.7
hornblende	14	56.7
pyroxene	24	12.3
ore	2	0.4
sphene	1.8	—
apatite, garnet, etc.	2.2	0.8
Colour index	(44)	(79)

A certain number of the so-called " minettes " are dyke-shonkinites. Here is the composition of (1) a minette from Haö, Norway, according to W. C. Brögger, and beside it is the mode of a syenite porphyry (2) from Montana (L. V. Pirsson).

	(1)	(2)
soda-orthoclase (microcline)	51.5	64.6
biotite	26.5	10.4
diopside	16.5	13.5
magnetite	—	8.5
sphene	2.7	—
apatite	2.7	3.0
Colour index	(48)	(35)

Coming now to the *monzonites,* W. C. Brögger gives the following statement of the mineralogical composition of the typical monzonite of the Tyrol :—

quartz	2.5	pyroxene	15.5
soda-orthoclase	30.0	magnetite	3.0
plagioclase (Ab_3 An_2)	32.0	apatite	2.0
biotite	10.0	sphene, zircon	1.0
hornblende	5.0	Colour index	(35)

Very close to this is the mode of a monzonite occurring on Salmon River, British Columbia, described by R. A. Daly :—

quartz	0.5	diopside	20.1
soda-orthoclase	32.6	magnetite	1.2
labradorite	27.9	apatite	0.8
biotite	16.9	Colour index	(39)

L. V. Pirsson has described monzonites in the Belknap Mountains of New Hampshire (1); at Highwood Peak (2), and Yogo Peak (3), Montana. In each case the rock is associated with a more leucocratic syenite.

	(1)	(2)	(3)
orthoclase			16.2
soda-orthoclase	20.0	33	
albite			30.1
plagioclase	27.2	25	
anorthite			11.3
biotite	1.0	10	12.1
hornblende	35.3	—	4.5
diopside	—	30	20.7
ore	14.8	2	5.1
apatite	1.7	—	—
Colour index	(53)	(42)	(42)

Monzonites occur in the district of Ben Nevis and Glen Coe, Scotland, and have been described by J. J. H. Teall and E. B. Bailey. A monzonite in Glen Creran carries some 50 per cent. of dark minerals, consisting as usual of pale green diopside intergrown with brown hornblende and biotite. The felspars are plagioclase and anorthoclase.

The lavas that are associated with monzonites in British Columbia, Sierra Nevada, and elsewhere are all leucocratic (trachyandesites). No example of a mesotype lava (trachybasalt) has been traced.

Subaluminous Type.

Few examples of subaluminous shonkinite or monzonite have been noted. In the following instance, described by C. W. Drysdale, the proportion of hornblende and biotite is so small that the rock may be considered to be subaluminous. An augite syenite at Franklin, British Columbia, has a coarse-grained marginal facies composed of large augite crystals, rising to an inch in diameter, set in a groundmass of smaller augite crystals with interstitial orthoclase. The mode is

orthoclase	17.1	ore	6.0
biotite	0.8	apatite	1.0
hornblende	1.5	sphene	0.4
augite	73.1	Colour index	(83)

A rock which W. N. Benson calls augite-diorite, occurring at Houghton, South Australia, may be a subaluminous monzonite. It carries oligoclase, microcline and orthoclase, along with diopside, sphene, apatite and ore. The norm is

quartz	2.5	diopside and hypersthene	17.5
orthoclase	11.1	ilmenite and hematite	7.4
albite	45.0	sphene	3.9
anorthite	10.8	apatite	1.3

Peralkaline Type.

This type is also uncommon. One of the rocks of Rainy River, Ontario, which A. C. Lawson included in the "malignite" group, is made up of orthoclase and blue-green soda-hornblende with subordinate biotite, soda-diopside, sphene and apatite; if no unsaturated mineral is present, this is a shonkinite. W. C. Brögger has described melanocratic syenites (shonkinites) at Tveitasen and Melteig in Norway and V. Hackmann a very similar rock at Ahvenvaara, Finland. The modes are given in that order.

	(1)	(2)	(3)
orthoclase	7.7	19.2	18.0
albite	7.4	34.3	27.5
soda-pyroxene	71.6	41.8	37.0
apatite	5.6	1.8	14.1
sphene	4.0	0.9	4.0
rest	3.2	1.2	1.9
Colour index	(82)	(44)	(57)

C. Diorites and Andesites.

The most leucocratic type of diorite is represented by certain rocks which are known as oligoclasite, plagioclasite, or generally as anorthosite, and which consist mainly of plagioclase felspar. Many anorthosites have been said to be "almost entirely composed of felspar," but in point of fact there is rarely less than four or five per cent. of dark minerals present. One has only to study the norms of the anorthosites and labradorite-rocks in Washington's Tables, to see that rocks with quite a high colour index have often been described under these names. For example, an anorthosite from New South Wales has 25 per cent. of femic constituents in its norm; one from Bohemia has 27 per

cent. of femic minerals, and one from Norway has 28½ per cent. of normative diopside, olivine, and ore. Since no anorthosite in the Tables has less than 2.6 per cent. of femic constituents in its norm, it seems that freedom from dark minerals is not more marked among anorthosites than it is among granites.

One of the most leucocratic of diorites is the badly-named "albitite" of Pala, California. The norm given in Washington's Tables shows quartz 9, orthoclase 1, albite 46.6, anorthite 40.9, with only 1.7 per cent. of femic constituents, apparently represented in the rocks by a little mica.

Probably no rock-name has been so abused as andesite. If one studies the norms of the "andesites" in Washington's Tables, one finds that quartz is frequently present in quantities greater than 20 per cent., rising to 35 per cent. In other cases there is such a deficiency of silica that 15 per cent. of olivine, or 11 per cent. of nepheline, appear in the norm. The ratio of orthoclase to anorthite reaches such values as 30 to 1 and 15 to 1, while in some cases anorthite is entirely absent and the norm contains acmite. The proportion of femic minerals in the norm varies from 5 to 50. In our classification, these rocks would be spread over rhyolite, rhyodacite, dacite, trachyte, trachyandesite, basalt, and certain undersaturated groups, and certainly less than half of them would be left in andesite. But most descriptions of rocks that are called "andesite" are so imperfect that it is impossible to place the rocks properly in a quantitative classification.

Peraluminous Type.

Diorites of peraluminous type are little known. Many rocks are described loosely as "mica-diorite," but it generally appears on investigation that such rocks either hold far too much quartz to be diorites at all, or else they carry hornblende as well as biotite. Among dyke-rocks, the "kersantite" group is characterised by the association of plagioclase with biotite, but when quantitative data are available these rocks generally show more than 30 per cent. of dark minerals.

The "albitite" of Pala, California, mentioned above, is apparently a genuine mica-diorite.

Peraluminous andesites possibly exist, but it is very difficult to recognise them among the "mica-andesites" that have been described. Nearly all so-called mica-andesites carry hornblende

or augite as well as mica, and, in addition, many of them are far too siliceous to deserve the name of andesite at all.

Metaluminous Type.

The Marcy anorthosite, of the Adirondack Mountains of New York, is a metaluminous lime-diorite in our classification. It is composed of large blue-gray labradorite crystals, averaging about an inch in diameter, together with 5 to 10 per cent. of hornblende, pyroxene, biotite, ilmenite, pyrite, garnet, and sometimes iron and copper sulphides (W. J. Miller). In typical anorthosites such as this, the felspar is a very calcic variety and quartz is totally absent. More sodic types are also known, in which both orthoclase and quartz are present.

Soda-diorite accompanies granodiorite and tonalite in Montana. The Pinto diorite, in the Little Belt Mountains, has the following composition, according to L. V. Pirsson :—orthoclase 17.5, andesine 63.5, hornblende 13, biotite and apatite 3.5, ore 2.5 per cent. (Colour index 19.)

The Haystack tonalite, in the same state, has a soda-diorite facies, for which the following mode is furnished by W. H. Emmons :—

quartz	6.8	olivine	0.5
orthoclase	15.4	biotite	4.6
albite	27.5	iron ores	5.2
anorthite	19.7	apatite	0.8
pyroxene	19.5	Colour index (31 by weight)	

Here we have a case of incomplete reaction, such as we have already discussed, leading to the appearance of quartz and olivine together; but there is more than enough quartz to have converted all the olivine into pyroxene, so we regard the rock as a saturated one. The colour ratio is slightly over 30 per cent. by weight, or 27 per cent. by volume.

Diorites of very variable composition occur at Electric Peak, Yellowstone National Park, according to J. P. Iddings. Both hypersthene and augite are present, along with hornblende which often surrounds the pyroxene crystals, biotite, plagioclase, orthoclase and quartz. Some of these rocks are certainly too dark to fall into this group, and others are too siliceous.

F. R. van Horn described a quartz-hypersthene diorite at Ivrea, Piedmont, which carries some brown and green hornblende in addition to hypersthene and medium plagioclase. A little

quartz is also present. The norm shows quartz 9.2, orthoclase 6.1, albite 33.5, anorthite 32, with 19 per cent. of femic constituents.

W. G. Foye describes a variety of " gabbro " on the island of Vanua Levu, Fiji, which consists of zoned plagioclase crystals (85 per cent.) with 14 per cent. of augite and fibrous hornblende, and a little ore. This rock falls into diorite in the present scheme of classification.

The " labradorite norite " of Flakstadö, Norway, which has been the subject of detailed study by J. H. L. Vogt, is also rather too leucocratic to be a typical norite. It has insets of plagioclase of the composition $An_{61}Ab_{33}Or_6$ in a groundmass of more sodic plagioclase ($An_{52}Ab_{42}Or_6$) with pyroxenes, biotite and ore. The mode is

plagioclase (weight)...	70.6	biotite	2.3
hypersthene	10.0	ore	7.0
diallage	10.0	apatite	0.1

The colour ratio is 29.4 per cent. by weight, or about 27 per cent. by volume, so the rock is classed here as a lime-diorite.

Metaluminous andesites, containing hornblende and biotite, have been described, for example, in the Siebengebirge of the Rhine, in Hungary, Spain, the Andes, Central America, and the United States, but quantitative detail is mostly lacking. Many of those rocks are certainly rhyodacites and trachyandesites.

Hornblende-hypersthene andesites have been described on Lassen Peak and Mount Shasta in California, Mount Rainier in Washington, and Mount Hood in Oregon, but so far as one can judge from the norms, these rocks should be classed as dacite.

The lavas of Electric Peak and Sepulchre Mountain, in the Yellowstone National Park, are mostly too acid to be admitted to the group of andesites as defined here, and some of them have orthoclase in excess of anorthite; but about four of the analyses given by J. P. Iddings represent slightly oversaturated rocks with anorthite greater than orthoclase and a colour index apparently about or rather less than 30. Some of these rocks are microcrystalline, but many have a residue of dark glass. Augite, hornblende and biotite all appear among the dark minerals. Hornblende is present in almost every case, and the more hornblende, the less pyroxene does the rock carry. Biotite

accompanies the hornblende in those rocks which hold least pyroxene.

Subaluminous Type.

The "andesine anorthosite" of Amherst County, Virginia, described by Watson and Cline, is a subaluminous soda-diorite. It is composed of andesine and some microcline, with subordinate blue quartz and a little hypersthene, rutile, ilmenite and apatite. The norm is quartz 5.7, orthoclase 20, albite 40, anorthite 28, with only 2.8 per cent. of femic constituents.

A number of rocks which have been described as quartz-gabbro, quartz-norite, and quartz-dolerite, are sufficiently leucocratic to fall into diorite. The gabbro of Carrock Fell, Cumberland, which has been studied by A. Harker, has an acid facies with specific gravity less than 2.85; this carries micropegmatite and a few quartz grains. Judging from the specific gravity and the chemical composition, the colour index cannot be more than about 20, which brings the rock into diorite in our system. It may be remarked that this rock, which Harker calls quartz-gabbro, was earlier described by T. H. Holland as augite-diorite. In the same way, the intrusion at Penmaenmawr, North Wales, which L. Schaub referred to quartz-norite, was earlier described by J. J. H. Teall as enstatite-diorite, and according to Schaub's analyses, it is sufficiently leucocratic to remain in the diorite group.

J. V. Harrison has described a "quartz-dolerite" in the Kilsyth Hills, Scotland, which must for the same reason be placed in diorite. The following mode is given:—

felspar and micropegmatite ...	78
augite	14.8
magnetite	4.6
pyrites	1.0
apatite	0.5
serpentine	1.1
Colour index	(22)

Subaluminous andesites are probably commoner than any other type, although a large proportion of the rocks that have been described as augite-andesite and hypersthene-andesite have a colour index greater than 30, and are consequently to be transferred to basalt.

The andesite of Pasto Volcano in Colombia, described by R. Küch, has the following mode :—

quartz	8.9	augite	14.0
orthoclase	9.4	magnetite	8.5
albite	14.9	apatite	0.3
plagioclase (Ab_7 An_9)	43.9	Colour index	(23)

The andesites of the San Francisco volcanic district in Arizona, described by H. H. Robinson, are interesting as showing olivine crystals in a glassy base which contains free silica. In the following table the actual mineral composition of these rocks is given, together with the calculated composition :—

		San Francisco Mtn.	*Kendrick Peak*
Actual development of rock	Groundmass	27.7	32.2
	Felspar	52.9	53.2
	Pyroxene	10.4	7.4
	Olivine	2.4	4.2
	Magnetite	6.6	3.0
Calculated composition of entire rock	Quartz	10.1	8.6
	Orthoclase	13.1	12.8
	Albite	35.6	33.0
	Anorthite	19.2	18.5
	Augite	8.0	9.3
	Hypersthene	3.6	5.5
	Olivine	2.4	4.3
	Magnetite	6.9	6.5
	Apatite	1.0	0.7
	Colour index	(23)	(27)

The first of these is a dark gray, compact or vesicular rock, with little insets of plagioclase which seldom exceed 1 millimetre in diameter. The groundmass shows little felspar laths, grains of pyroxene, tiny olivine grains, magnetite and glass. In each of these rocks there is enough free silica to have converted all the olivine into hypersthene, if cooling had taken place with sufficient slowness to allow the reaction to take place. If we perform this operation on paper, the first rock will be enriched by 3.4 per cent. of hypersthene, leaving 9 per cent. of quartz; and the second will have altogether 11.6 per cent. of hypersthene and 6.7 per cent. of quartz. Both rocks are therefore abnormally developed andesites.

D. Gabbros and Basalts.

The oldest name for a plagioclase rock containing a large proportion of either pyroxene or hornblende is "diabase" (Brongniart). This was followed by "gabbro" (von Buch) for more coarse-grained rocks of the same mineralogical character, and by "dolerite" (Haüy) for the geologically younger diabases. "Norite" (Esmark) is a later name for gabbro containing an orthopyroxene. Here are four names in use where one would be sufficient. Gabbro and norite differ only in a minor mineralogical character, which is disregarded in the naming of other classes of rocks. Diabase and dolerite are synonymous, and differ from gabbro and norite only in respect of an inconstant textural feature. If such minor differences as these were recognised by the creation of new specific names in other classes of rocks, our stock of names would rise rapidly from the hundreds into the thousands. There seems to be a clear case for the abolition of either gabbro or norite; especially since the discovery of the enstatite-augite series of pyroxenes, which are intermediate in character between augite and enstatite; and for the disuse of dolerite and diabase except perhaps as geological field terms. Some dolerites and diabases are so fine-grained as to be indistinguishable from basalts; others are coarse enough to be called gabbro. The terms "dyke-gabbro" and "dyke-basalt" describe these rocks quite adequately.

Peraluminous Type.

Peraluminous gabbro is almost unknown, if the corundum-biotite-plagioclase rocks are considered to be undersaturated with silica. A rock that seems to fulfil the requirements of this group, although the mode has not been stated in quantitative terms, is the "mica-diorite" of Namaqualand, S. Africa. According to A. W. Rogers, this rock holds about 60 to 65 per cent. of plagioclase, and a chemical analysis by E. G. Radley indicates that the proportions of the constituent minerals are approximately as follows:—

felspar (about Ab_1An_1)	65
biotite	11.5
oxides of iron and titanium	19
sulphides of iron and copper	1.5
decomposition products and accessory minerals	3
Colour index (35)	

In this instance it is not the proportion of biotite but the unusually large amount of iron ores that takes the rock over to the mesotype group.

Effusive basalts rarely, if ever, belong to this type, but among the fine-grained dyke rocks the kersantite variety has the composition of peraluminous basalt. These rocks consist typically of plagioclase and biotite, but quantitative mineralogical data are seldom available. J. H. L. Vogt gives the composition of a kersantite at Bygdö, Sweden, in the following terms :—

labradorite	60 to 70 per cent.
biotite	20 to 25 ,,
magnetite	10 to 12 ,,
pyrite	2 to 3 ,,
apatite	1.4

Colour index (30 to 35)

Metaluminous Type.

A hornblende gabbro which is almost free from pyroxene has been described by I. S. Allison in the Giant's Range of Minnesota. It consists roughly of 70 parts of labradorite and 30 parts of hornblende (with occasional pyroxene cores) and traces of magnetite and apatite.

The gabbro of Prentice Mountain, Connecticut, described by G. F. Loughlin, has the following composition :—

quartz	6	biotite	2
plagioclase (Ab_1An_1)	45	ore	5
hornblende	41	apatite	0.5
		Colour index	(49)

A gabbro which F. Sellner described (under the name of diorite) from the Galgenberg, in the Brünner massif, Austria, is remarkably close to the last in mineralogical composition. It contains

quartz	8.8	biotite	1.6
plagioclase	46.0	sphene and ore	2.5
hornblende	40.6	apatite	0.5
		Colour index	(45)

Hornblende gabbros have been observed by S. W. Wooldridge on the island of Sark, Channel Islands. Some of the rocks are said to be "virtually dimineralic, consisting simply of oligoclase and hornblende." In one case, measurements indicated 48 parts of oligoclase and 50 of hornblende. These rocks are associated with granites and other oversaturated rocks, and

Wooldridge thinks that assimilation of schists is the cause of the production of these strongly hornblendic facies.

Gabbros that are rich in mica are less common. A good example has been described by W. Campbell Smith, in South Victoria Land. The mode is as follows :—

quartz	2	biotite	23
orthoclase	4	hornblende	17
albite	29	sphene	3
anorthite	17	magnetite	1.5
		Colour index	(44)

F. Sellner describes mica-rich gabbros (called diorites) in the Brünner massif, Austria. Two modes are given :—

quartz	4.5	5.0
plagioclase	47.5	48.8
biotite	23.9	19.9
hornblende	22.7	24.6
accessories	1.4	1.7
Colour index	(48)	(46)

Most metaluminous gabbros hold either ortho- or clino-pyroxene in addition to hornblende or biotite.

The hornblende-gabbro of Frankenstein, Germany, has been examined by P. Tschirwinsky, who finds the composition to be as follows :—

plagioclase (An_{35} to An_{55})	62.2	(volume)
augite	29.9	
hornblende	6.2	
titanomagnetite	1.6	
pyrites	0.1	
Colour index	(38)	

The hypersthene-hornblende association is illustrated by the " norite " of St. Thomas' Mount, Madras, for which H. S. Washington gives the following mode :—

plagioclase (Ab_1An_1)	40.8	hornblende	19.6
hypersthene	31.0	ores	8.6

The hypersthene-biotite association is encountered in many of the " norites " of Norway. The rock of the Skougen mine at Bamle holds 48 parts of plagioclase with 47 of hypersthene (including a little secondary hornblende), 4 of biotite, and a little apatite and ore. The rock of the Höiaas mine, Tvedestrand, has 62 per cent. of labradorite with 33 of hypersthene and 3 of biotite (J. H. L. Vogt).

The association of hornblende, augite and biotite is seen in the gabbros of Slesse Mountain and Ashnola, British Columbia (R. A. Daly), and in the " diorite " of Belknap Mountain, New Hampshire (L. V. Pirsson).

	Slesse Mtn.	*Ashnola.*	*Belknap Mtn.*
quartz	9.5	0.5	—
labradorite	58.0	57.5	43.5
biotite	12.5	3.0	3.3
hornblende	12.8	21.8	26.3
augite	4.3	12.0	15.8
ores	2.3	3.6	7.7
accessories	0.6	1.6	3.4
Colour index	(32)	(42)	(56)

The same association appears in the gabbro (" augite-diorite ") of Monzoni, described by C. Doelter. From an analysis of this rock the following mode is calculated :—

orthoclase	10—12	pyroxene	20—25
plagioclase	50—55	hornblende, biotite	5—10
magnetite	7—10		

Hypersthene occurs together with augite and biotite in the norite of Tripyramid Mountain, New Hampshire. The mode, according to L. V. Pirsson, is :—

quartz	3.0	augite	5.6
plagioclase	56.5	biotite	6.0
orthoclase	3.0	ore	11.0
hypersthene	10.0	apatite	4.4
		Colour index	(37)

Gabbros with a very high hornblende content have been described by R. A. Daly in the Purcell Mountains, British Columbia. The modes of two of these rocks are stated as follows :—

quartz	4.0	6.3
plagioclase	34.8	25.6
hornblende	58.7	54.8
biotite and chlorite	0.9	11.0
sphene, magnetite, apatite	1.6	2.3
Colour index	(61)	(68)

Other highly melanocratic gabbros are described by W. G. Foye at Glamorgan, Ontario (1), and by G. A. Young at Mount Yamaska, Quebec (2, 3).

	(1)	(2)	(3)
plagioclase ...	22.6 (weight)	26.9 (volume)	15.0 (volume)
hornblende	44.3	34.9	21.2
augite	19.5	20.1	43.4
ilmenite	12.2	18.1	16.7
pyrites	—	—	2.4
apatite	1.2	—	1.3
Colour index ..	(75)	(73)	(85)

F. R. van Horn describes a melanocratic gabbro at Ivrea, Piedmont, and gives the following statement of the mode, which he determined by mechanical separation of the constituents :—

bytownite	33	hypersthene	5
hornblende	27	magnetite	10
diallage	20	spinel	5
		Colour index	(67)

Melanocratic hornblende- and biotite-norites are described by J. H. L. Vogt, in Norway. A rock occurring at Litvandet, Hosanger, has 20 per cent. of labradorite, with 60 of pyroxene, 12 of hornblende, 5 of biotite and a little pyrrhotite and apatite. (Colour index about 80.) The norite of Romsaas holds 3 to 4 per cent. of quartz along with 22 to 24 of plagioclase, 64 of orthopyroxene, and 8 to 10 of biotite. (Colour index about 74.)

Norites that have been greatly contaminated by solution of aluminous sediments, leading to the appearance of cordierite, garnet and other highly aluminous minerals have been described by H. H. Read and W. R. Watt in north-eastern Scotland. The mode of one such rock, occurring near Huntly, has been given as follows by Watt :—

quartz	1.0	hypersthene	3.0
orthoclase	2.8	garnet	16.6
albite	30.9	cordierite	14.4
anorthite	12.2	sillimanite	0.2
biotite	13.5	ilmenite, etc.	4.8
		Colour index	(36)

Metaluminous basalts are much less common than the corresponding gabbros. A hornblende basalt is described by H. H. Robinson at Bill Williams Mountain, Arizona. The visible constituents of this rock are hornblende (48 per cent.), labradorite (12 per cent.) and magnetite (2 per cent.), with a cryptocrystalline groundmass which makes up 37 per cent. of the rock. If the

rock had crystallised completely, it would have had approximately the following composition :—

quartz	7.1	hornblende	47.6
orthoclase	4.4	magnetite	2.0
albite	29.8	apatite	.3
anorthite	8.2	Colour index	(50)

Among dyke-basalts, however, it is likely that many examples of this type could be found. Such are, for instance, many of the so-called " camptonite " dykes. Pirsson and Washington have described a camptonite at Mount Belknap, New Hampshire, which consists of

labradorite	53.2	apatite	1.9
hornblende	31.7	calcite	6.7
iron ore	6.4	Colour index about 40	

Subaluminous Type.

Many rocks of this type are exactly saturated, but others hold a little interstitial micropegmatite. A good example of this kind is the big intrusive sheet called the Whin Sill in the north of England. This sheet varies a good deal from place to place, as regards both composition and texture, but the coarser facies hold both ortho- and clino-pyroxene, and a little hornblende or a trace of biotite may be present too. According to J. J. H. Teall, quartz may always be detected as an original mineral, occurring partly in independent grains and partly in micropegmatite. Teall gives the following estimate of the mineral composition of the Whin Sill : quartz 9, orthoclase 7.5, albite 21.5, anorthite 13, pyroxene 36, ore 7, apatite 1, rest 4.8 per cent. The colour index is therefore about 45.

Similar rocks were described by T. H. Holland in Madras, India, under the name of " augite diorite." They consist of augite and plagioclase, with an interstitial micropegmatite composed of quartz and either plagioclase or microcline. The proportions of the essential minerals indicated by a single chemical analysis are as follows : quartz 10, orthoclase 9.4, albite 10, anorthite 33.4, pyroxenes 23.7, ores 9, apatite 3.7.

Such quartz-bearing gabbros and dolerites have been widely recognised in Scotland, Sweden, Canada, the eastern states of America, British Guiana, South Africa and Tasmania, where they form thick sheets and dykes. G. W. Tyrrell states the composition of a dyke in the west of Scotland in the following

terms :—micropegmatite 10.2, plagioclase 53.2, ortho- and clino-pyroxene 27.1, ore 6.3.

W. H. Collins describes sills of "quartz-norite" in the Onaping area, Ontario, as consisting of approximately equal parts of plagioclase and pyroxene, with a little titanomagnetite and up to 15 per cent. of a micropegmatite of quartz with acid plagioclase. Collins shows that the presence of micropegmatite is related to the coarseness of the rock. When the grain of the rock is less than a quarter of a millimetre, no micropegmatite is seen, but the coarser the grain, the more micropegmatite is present.

The Palisade sill, which has an outcrop of more than a hundred miles in New York and New Jersey, is also a quartz-bearing gabbro. According to J. V. Lewis, the constituent minerals are augite, plagioclase, quartz, orthoclase and magnetite, in that order of abundance.

The gabbro of West Rock, Connecticut, is almost exactly saturated. G. W. Hawes has given the mode as follows :—orthoclase 2.3, plagioclase 37.7, pyroxene (including both augite and enstatite) 54.5, ilmenite 2.7, magnetite 1.8, apatite 0.3 per cent. (Colour index 60.)

An extremely calcic rock is the lime-gabbro (lime-norite) described by F. Bascom in Cecil Co., Maryland. The mode is

orthoclase	0.3	hypersthene	39.7
albite	4.3	magnetite	1.6
anorthite	53.0	rest	1.3
		Colour index	(42)

Some gabbros and norites hold a very high proportion of titanic iron ore. The ore-bringer at Ekersund, Norway, is stated by Vogt and Kolderup to consist of plagioclase 21, hypersthene 41, and ilmenite 38 per cent.

H. S. Washington describes subaluminous andesite-basalts at Monte Arci, Sardinia. These are dense, dark gray or black rocks, showing only rare and very small insets of felspar. Both ortho- and clino-pyroxenes are present, and there is a very small residuum of siliceous glass. The following mode is calculated from a chemical analysis :—

quartz (in glass)	4	ores	8
Ab_7An_8	62	apatite	1
diopside	5	glass	3
hypersthene	17	Colour index about	31

Among the basalts of Monte Ferru, in the same island, there are some which show the association of quartz and olivine, of which we have already discussed several instances. The olivine crystals form insets only, while the quartz is confined to the interstitial base of the groundmass. In each case described by Washington, there is enough free silica to have converted the whole of the olivine into enstatite, as the following figures show :—

	(1)	(2)
quartz	5	4
Ab_1An_1	57	50
pyroxene	21	32
olivine	10	8
ores	6	5
apatite	1	1
Colour index	(37)	(46)

Washington has also described basalts on the isle of Pantelleria, one of which is composed of plagioclase $(Ab_3An_2)48$, augite 32, iron ores 17, and apatite 3 per cent. (Colour index 52.)

A. Harker describes an "andesite," or a basalt according to our system, on the island of Eigg, Scotland, which contains andesine 49, augite 37, titanomagnetite 13.5, and apatite 0.5 per cent. (Colour index 51.)

A. Holmes gives mineralogical analyses of some basalts from Iceland (1—3) and the Faroe Islands (4, 5) as follows :—

	(1)	(2)	(3)	(4)	(5)
plagioclase	63	49	48	45	42
pyroxenes	29	41	38	39	43
iron ore	8	9	10	12	13
glass	—	1	2.5	4	2
Colour index	(37)	(50)	(48)	(51)	(56)

The basalts of the Deccan, India, have lately been studied afresh by H. S. Washington. In a region of over 200,000 square miles some variation must be expected, but these basalts are remarkably similar all through the region. They are mainly dense, non-porphyritic rocks with not more than ten per cent. of glass. In the majority of cases olivine is entirely absent and there is a small excess of silica. Augite and labradorite make up about 90 per cent. of the rocks, and some magnetite is always present.

The following norms, calculated from two of Washington's analyses, give an idea of the mineralogical composition of the rocks :—

	(1)	(2)
quartz	5.5	2.4
orthoclase	5.6	6.7
albite	18.3	25.7
anorthite	21.1	24.5
pyroxene	35.1	35.1
magnetite and ilmenite	12.4	2.8
apatite	0.7	1.7

The Snake River basalts of Oregon are very similar to the Deccan " traps." The norm calculated from six analyses shows

quartz	2.2	pyroxene	32.7
orthoclase	7.8	magnetite and ilmenite	8.9
albite	24.6	apatite	2.0
anorthite	20.6		

An example of a melanocratic basalt, remarkably rich in iron oxide, is described by Washington and Larsen from North Park, Colorado. The rock is black, heavy, and very fine-grained. The microscope shows that it is holocrystalline and consists of magnetite, plagioclase, augite and a little apatite. The proportions of these minerals are magnetite 56, bytownite 25, augite 15, apatite 4 per cent. (Colour index 75.)

E. Perknites.

Under this name we include all saturated rocks which are composed, to the extent of ninety per cent. or more, of pyroxene, hornblende, or biotite, with which magnetite, ilmenite, chromite, spinel, or a sulphide may be associated. An iron-rich olivine or an iron-rich garnet may also be present. There are rocks that consist almost entirely of iron-ore (magnetite-rock, ilmenite-rock, chromite-rock); but as these are probably accumulations of solid ore particles, and did not crystallise from magma of their own composition, they are better regarded as ore-deposits than as eruptive rocks. We may therefore sub-divide the perknites as follows :—

Subaluminous type: characteristic minerals, diopside, augite, diallage, or ortho-pyroxene, with or without iron ores or fayalite. The general name for such a rock is *pyroxenite*.

Metaluminous type: characteristic minerals, (a) hornblende and biotite, with or without pyroxene and ore; (b) garnet, with pyroxene or hornblende. Rocks of the former character have usually been described as "hornblende-pyroxenite"; those with garnet as an important constituent are *eclogite*.

Peralkaline type: characteristic minerals, a soda-bearing pyroxene or amphibole.

Subaluminous Type.

A splendid example, illustrating a relation that very commonly exists between pyroxenite and the magma from which it is developed, is found in the parish of Gran, Norway. According to W. C. Brögger, there are in this parish several small bosses of "essexite," a rock composed of orthoclase, labradorite and augite, with a little olivine, hornblende and biotite. About the margins of these bosses, the augite has become concentrated at the expense of the other minerals, giving rise to a rock that consists of as much as 95 per cent. of augite, with only trifling quantities of hornblende, biotite and labradorite. Comparing the chemical composition of the pyroxenite with that of the essexite, it is apparent that there has been a movement of magnesia and lime towards the margin, and of alumina and alkalies in the opposite direction.

Pyroxenite consisting of ortho-pyroxene, with only trifling amounts (from one to six per cent.) of plagioclase, diopside and chromite, plays an important part in the deeper layers of the great norite sheet in the Transvaal. P. A. Wagner has described many thick sheets of such rocks, regularly interstratified with norite, olivine-norite, anorthosite, peridotite and serpentine, and apparently graduating into some of these. He explains the formation of this sheeted structure, which closely simulates the bedding of sedimentary rocks, by supposing that the earliest crystals to form in the original norite magma, namely those of olivine and chromite, sank on account of their high specific gravity and accumulated at lower levels, where the olivine was partly or wholly converted, by reaction with the residual magma, into pyroxene; thus giving rise to all possible intermediate types between pure olivine rocks and pure pyroxene rocks, with local accumulations of chromite.

Diopside-pyroxenites with only trifling proportions of biotite or hornblende have been described by W. C. Brögger at Monzoni, Tyrol. The modes of two such rocks are given below :—

plagioclase	7	6
diopside	80	82
biotite	3	4
hornblende	—	
magnetite	7	6
rest	3	2

The specific name " websterite " is sometimes used for pyroxenites which carry both ortho- and clino-pyroxenes. F. Bascom has described such a rock at Oakwood, Maryland, which consists simply of hypersthene (43 per cent.), diallage (56 per cent.) and a trace of some accessory minerals.

Many pyroxenites carry a moderate or even large proportion of oxidic or sulphidic ore. P. Geijer has described the passage of a syenite, at Rackberget, Sweden, into a rock composed of pyroxene, fayalite and magnetite in the proportion (to judge from a single text-figure) of about 50 : 20 : 30. The " Pusey iron ore " of Glamorgan, Ontario, is a heavy, black rock made up essentially of augite and titanomagnetite, the latter constituting from one quarter to over three quarters of the rock (Adams and Barlow). The pyroxene grains are completely enclosed in magnetite, but about each grain there is generally a narrow mantle of brown hornblende, which has been formed from the pyroxene.

Metaluminous Type.

A good example of this type is a hornblende-hypersthenite from Madras which was described by H. S. Washington. It is absolutely free from felspar, and consists of hypersthene 46, clino-pyroxene 5, hornblende 40.7, and magnetite 8.3 per cent.

At Mount Yamaska, one of the Monteregian Hills of Quebec, G. A. Young records the occurrence of a pyroxenite made up of pink, pleochroic pyroxene (evidently hypersthene) and reddish-brown hornblende, with a little anorthite, ore and accessory minerals. The precise composition of this rock is

anorthite	2	pyrites	1.0
pyroxene	57	apatite	0.2
hornblende	29	secondary	3.5
ilmenite	7.3		

It throws a curious light on the present state of petrographic nomenclature that these two rocks, so closely alike in all essential

characters, should have received distinct specific names (" bahiaite " and " yamaskite ").

The association of diopsidic pyroxene with hornblende and biotite is shown by a pyroxenite which J. Phemister describes, occurring near Loch Ailsh, Scotland. The pale green pyroxene amounts to 60.4 per cent., and it is associated with 19.2 per cent. of biotite, 11 of hornblende and 9.4 of iron ore. The hornblende in this rock typically encloses the pyroxene, and in the same district there are bodies of hornblende rock or hornblendite, composed of the same kind of hornblende that is found in the pyroxenite, but each crystal holds a little core of pyroxene.

Hornblendic rocks similar to the last were described by B. K. N. Wyllie and A. Scott at Garabal Hill, Scotland, under the name " davainite." The hornblende crystals either hold cores of diallage, or else the core has disappeared and the diallagic structure is preserved in hornblende. The proof is therefore complete that the hornblende was formed by transformation of pyroxene. The cause of the transformation is thought to have been the reheating of the original pyroxenite by later dioritic magma; but perhaps magmatic fluids, rather than magmatic heat, were the agents.

Many pyroxenites hold a little garnet. A. Lacroix has described dyke-rocks consisting of diopside and garnet, diallage and garnet, and diallage with hornblende and garnet, at Lherz, in the Pyrenees. The garnet is described as " grenat pyrope ferrocalcique."

When garnet becomes a large constituent of a pyroxenite, it is usual to give the name " eclogite " to the rock. The eclogites generally exhibit the striking combination of bright green pyroxene (diopside or chrome-diopside) with green hornblende and pink garnets. P. Eskola has studied the eclogites of Norway in great detail; the following mineralogical analysis of the eclogite of Silden was made by separating the crushed grains by means of heavy liquids :—

pyroxene	57.7	quartz and mica	7.9
garnet	34.1	rutile	0.3

The garnet was analysed and proved to contain the four oxides FeO, MnO, MgO, and CaO, in the ratio of 40 : 2 : 43 : 15, and Al_2O_3 : Fe_2O_3 as 94 : 6; thus the almandine and pyrope molecules predominate, with subordinate grossularite.

Peralkaline Type.

Perknites consisting mainly of soda-pyroxene, generally a more or less sodic diopside, have been found in connection with peralkaline syenites in several localities, such as Ice River, British Columbia, and Palabora, Transvaal.

REFERENCES.

Adams, F. D. and Barlow, A. E.—Canada, Geol. Survey, Mem. 6, 1910.
Allison, I. S.—Jour. Geol., 1925, *488*.
Bailey, E. B.—Scotland, Geol. Survey, Expl. 53, 1916, *170*.
Barrell, J.—U.S. Geol. Survey, Prof. Paper 57, 1907.
Bascom, F.—Maryland Geol. Survey, 1902.
Benson, W. N.—Trans. Roy. Soc. S. Australia, 1909, *122*.
Brögger, W. C.—(Akerite) Zeit. Kryst., 1890, *43*.
do. —(Gran) Quart. Jour. Geol. Soc., 1894, *15*.
do. —Eruptivgesteine des Kristianiagebietes, vols. I.-III.
do. —(Monzoni) Erupt. Kristianiagebietes, vol. II.
Clapp, C. H.—U.S. Geol. Survey, Bull. 704, 1921.
Collins, W. H.—Canada, Geol. Survey, Mem. 95, 1917.
Cross, W.—(Henry Mts.) U.S. Geol. Survey, 14 Ann. Rep., 1894, *227*.
do. —(Rosita Hills) U.S. Geol. Survey, 17 Ann. Rep., 1896.
Daly, R. A.—Canada, Geol. Survey, Mem. 38, 1912.
Doelter, C.—Tschermak's Min. Pet. Mitt., 1902, *73*.
Dresser, J. A.—(Shefford Mt.) Canada, Geol. Survey, Ann. Rep. 1902.
do. —(Brome Mt.) Canada, Geol. Survey, Ann. Rep., 1906.
Drysdale, C. W.—Canada, Geol. Survey, Mem. 56, 1915.
Duparc, L. and Pamfil, A.—Bull. soc. min. France, 1910, *369*.
Eggleston, J. W.—Amer. Jour. Sci., 1918, *377*.
Emmons, W. H.—Jour. Geol., 1908, *212*.
Eskola, P.—(Eclogite) Videnskaps Selskabets Skrifter, 1921, no. 8.
do. —(Orijärvi) Finland, Comm. Geol., Bull. 40, 1914.
Foye, W. G.—(Glamorgan) Econ. Geol., 1916, *662*.
do. —(Fiji) Proc. Amer. Acad. Arts Sci., 1918, *1*.
Geijer, P.—Geol. Fören. Förhandl., 1912.
Grout, F. F.—Jour. Geol. 1925, *467*.
Hall, A. L.—Trans. Geol. Soc., S. Africa, 1912, *4*.
Harker, A.—(Carrock Fell) Quart. Jour. Geol. Soc., 1894, *311*.
do. —(Skye) Scotland, Geol. Survey, 1904.
Harrison, J. V.—Trans. Geol. Soc. Glasgow, 1915, *327*.
Hawes, G. W.—U.S. Geol. Survey, Educ. Bull. 150, *273*.
Holland, T. H.—Quart. Jour. Geol. Soc., 1897, *405*.
Holmes, A.—Quart. Jour. Geol. Soc., 1917, *222*.
Iddings, J. P.—U.S. Geol. Survey, 12 Ann. Rep., 1891, *569*.
Jensen, I. H.—(Canobolas Mts.) Proc. Linn. Soc. N.S.W., 1909, *157*.
do. —(Mt. Flinders) do. 1909, *67*.
do. —(Glasshouse Mts.) do. 1906, *169*.
Kerr, H. L.—Ontario, Bureau of Mines, 19 Ann. Rep., 1910, *194*.
Kolderup, C. F.—Bergens Museums Aarbog, 1896, 1903.
Küch, R.—Reiss and Stübel, Reise in Sud-Amerika, 1892, *139*.
Lacroix, A. (Pyrenees) France, Carte geol., Bull. 42, 1895, *20*.
do. (Madagascar) Mineralogie de Madagascar, Paris, 1922.

Lawson, A. C.—Bull. Dept. Geol. Univ. California, 1896, *337*.
Lewis, J. V.—New Jersey, Ann. Rep. State Geologist, 1907.
Logan, W.—Geol. of Canada, 1863, *655*.
Loughlin, G. F.—U.S. Geol. Survey, Bull. 492, 1912.
Marshall, P.—Quart. Jour. Geol. Soc., 1906, *329*.
Mennell, F. P.—Geol. Mag., 1902.
Miller, W. J.—Bull. Geol. Soc., Amer., 1918, *399*.
Phemister, J.—Scotland, Geol. Survey, Expl. 103, 1926, *41*.
Pirsson, L. V.—(Little Belt Mts.) U.S. Geol. Survey, 20 Ann. Rep., 1900, *257*.
do. —(Highwood Mts.) U.S. Geol. Survey, Bull. 237, 1905.
do. —(Tripyramid Mt.) Amer. Jour. Sci., 1911, *405*.
do. and Washington, H. S.—(Mt. Belknap) Amer. Jour. Sci., 1906, *493*.
Quensel, P. D.—Bull. Geol. Inst. Upsala, 1914, *129*.
Ramsay, W. and Hackmann, V.—Fennia, vol. XI., 1894.
Read, H. H.—Scotland, Geol. Surv. (Geology of Huntly), 1923.
Robinson, H. H.—U.S. Geol. Survey, Prof. Paper 76, 1913.
Rogers, A. W.—Proc. Geol. Soc. S. Africa, 1916, xxi.
Schaub, L.—Neues Jahrb. Min., 1905, *93*.
Sellner, F.—Tschermak's Min. Pet. Mitth., 1922, *141*.
Shand, S. J.—Trans. Geol. Soc. S. Africa, 1921, *232*.
Smith, W. C.—Rep. Brit. Antarctic Exped., 1910, *206*.
Teall, J. J. H.—(Whin Sill) Quart. Jour. Geol. Soc., 1884, *640*.
do. —(Penmaenmawr) British Petrography, 1888, *272*.
Thomas, H. H.—Quart. Jour. Geol. Soc., 1911, *175*.
Tschirwinsky, P.—Centralblatt Min., 1925, *277*.
Tyrrell, G. W.—Geol. Mag., 1909, *362*.
Van Horn, F. R.—(Ivrea) Tschermak's Min. Pet. Mitt., 1897, *331*, *391*.
do. —(Pavone) Amer. Geologist, 1898.
Vogt, J. H. L.—(Flakstadö) Quart. Jour. Geol. Soc., 1909, *81*.
do. —(Norites) Norsk. Geol. Tidskrift, 1918, *194*.
Wagner, P. A.—S. Africa, Geol. Survey, Mem. 21, 1924.
Washington, H. S.—(Monte Arci) Amer. Jour. Sci., 1913, *577*.
do. —(Pantelleria) Jour. Geol., 1914, *653*.
do. —(Deccan) Bull. Geol. Soc. Amer., 1922, *765*.
do. —(Charnockite) Amer. Jour. Sci., 1916, *323*.
do. —(Plauen) Amer. Jour. Sci., 1906.
do. —(Bolsena) Jour. Geol., 1807, *350*.
do. —(Monte Ferru) Amer. Jour. Sci., 1915, *513*.
do. —(Roman Region) Carnegie Inst. Washington, Publ. 57, 1906.
do. and Larsen, E. S.—Jour. Wash. Acad. Sci., 1913, *449*.
Watson, T. L. and Taber, S.—Virginia Geol. Survey, Bull. III., 1913.
Watt, W. R.—Quart. Jour. Geol. Soc., 1914, *276*.
Weed, W. H. and Pirsson, L. V.—(Bearpaw Mts.) Amer. Jour. Sci., 1896, *136*.
do. —(Shonkinite) Bull. Geol. Soc. Amer., 1895, *389*.
Wooldridge, S. W.—Geol. Mag., 1925, *241*.
Wright, C. W.—U.S. Geol. Survey, Prof. Paper 87, 1915, *40*.
Wright, F. E.—(Massachusetts) Tschermak's Min. Pet. Mitt., 1900, *308*.
Young, G. A.—Canada, Geol. Survey, Ann. Rep., 1906, pt. H.

CHAPTER XII.

THE UNDERSATURATED ROCKS.

PART I. GENERAL.

So many different mineral associations are possible in this class that no general statement of geological occurrence can be made regarding the class as a whole, save this, that with a few striking exceptions, the undersaturated rocks occur in relatively small bodies, and are frequently connected by gradual transition with a saturated or oversaturated mass.

There are five distinct cases to be considered in this class, according to whether the deficiency of silica affects magnesia, soda, potash, lime or alumina. The characteristic minerals, in each case, are as follows :—

(1) olivine
(2) nepheline, sodalite, hauyne, nosean, cancrinite, analcime
(3) leucite
(4) melilite, melanite, scapolite, vesuvianite, wollastonite, calcite
(5) corundum, spinel

The Geology of Olivine Rocks. The largest bodies of undersaturated magnesian rocks are those in which felspar predominates and olivine plays quite a minor part, such as olivine-gabbros, olivine-norites, and olivine-basalts. One of the largest known masses of this type is the olivine-norite which builds the peninsula of Sierra Leone, West Africa. It has been studied by F. Dixey. The peninsula alone has an area of over two hundred square miles, and the same kind of rock reappears in the Banana Islands, showing that the norite continues far out to sea; its total area may be in the neighbourhood of four hundred square miles. This great intrusion must be regarded as a true batholith. The proportion of olivine is only ten to fifteen per cent., and it is distributed with fair uniformity through the whole mass of the rock. In places, the rock has a tendency to be banded, in consequence

of movements during freezing, some of the bands being more felspathic and others more melanocratic than the average rock; only in exceptional cases has there been a segregation of bands of nearly pure olivine, or thin seams of magnetite.

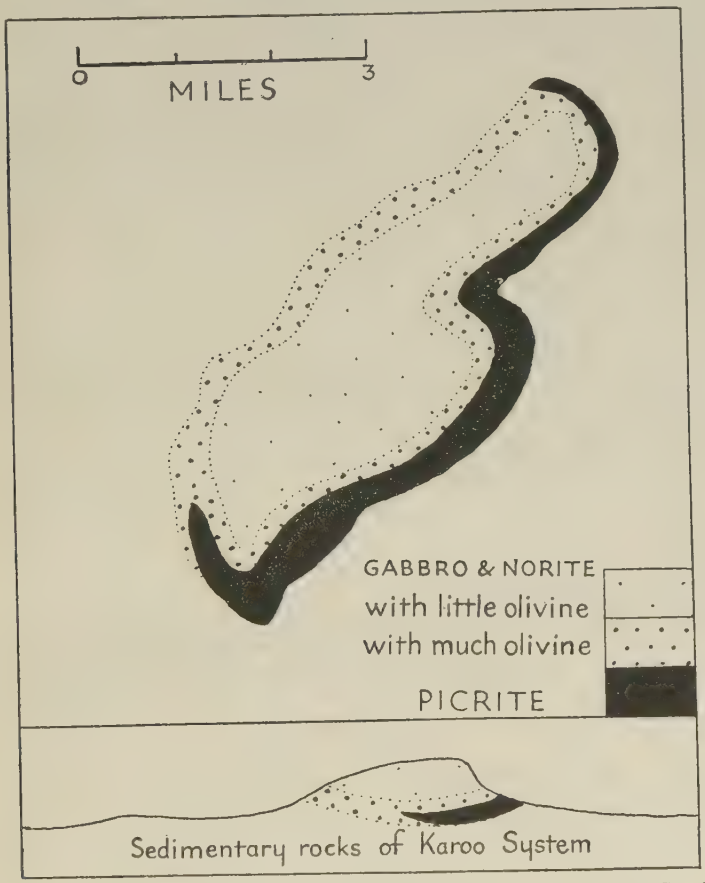

FIG. 27. Plan and section of Tabankulu Mountain, Pondoland, South Africa. (After A. L. du Toit.)

In other large intrusions of this type of rock, there has been a distinct gravitation of olivine towards the base of the intrusion, leading sometimes to the production of bodies of nearly pure olivine and pyroxene. This is well seen in the Insizwa intrusion, in South Africa, which has the form of a curved sheet, half-a-mile thick. According to A. L. du Toit, the rock is an acid gabbro

at the top, containing interstitial quartz and orthoclase. This passes down quite gradually into olivine gabbro and olivine norite, and towards the base of the sheet the rock is a picrite, containing more than half its bulk of olivine. The neighbouring Tabankulu intrusion is olivine-bearing throughout its entire thickness, but the concentration of olivine increases steadily downwards, the specific gravity of the rock being 2.91 at the top and 3.27 at the base. (*Fig.* 27.)

A more complete separation of olivine is demonstrated by the Palisade sill, which outcrops for about a hundred miles in New York and New Jersey. The thickness of this sill is in places as much as a thousand feet, and the main mass of the rock is a dolerite (diabase) entirely free from olivine and holding from five to twenty per cent. of quartz (J. V. Lewis). In the rapidly chilled marginal facies at top and base of the sheet a small quantity of olivine is present, showing that the original magma was slightly undersaturated. About fifty feet above the base of the sill there is a layer of olivine-diabase, from ten to twenty feet thick, in which nearly the whole of the olivine of the magma has been concentrated.

A still more remarkable case of a composite intrusion, consisting of alternate felspathic and peridotitic layers, is found in the island of Rum, Scotland, and has been described by A. Harker. In Allival Hill, Harker enumerates nineteen nearly horizontal layers of peridotite and allivalite alternately, the former consisting of olivine with only a little anorthite, and the latter of anorthite and olivine in roughly equal quantities. Harker says "it is scarcely possible to avoid the inference that these very different rocks have been derived from one ultimate source; that the olivine and anorthite molecules existed as such in the fluid magma, and that between these two there was, in effect, a decided mutual repulsion."

Instead of a segregation of olivine in horizontal layers, some bodies of gabbro and norite show concentration of olivine towards the centre (as seen in plan). In the Ural Mountains, peridotites and dunites (*i.e.*, pure olivine rocks) occur in distinct areas of relatively small size within large intrusions of gabbro and norite, some of the latter being olivine-bearing and some free from olivine. For instance, at Koniakowsky Hill, in the district of Nicolai-Pawda, an elliptical body of dunite, 1 x $\frac{3}{4}$ km., lies within an elliptical pyroxenite mass, 4 x 3 km., which is again completely surrounded by melanocratic gabbro, passing out into

normal gabbro (Duparc and Grosset). (*Fig.* 28.) Duparc maintains that the rocks of these concentric zones, from dunite to gabbro, are all differentiation-products of a single magma. In describing a similar occurrence at Solowiewa Hill, in the Tagil district, R. Spring seems to favour another view of the matter, for he writes that " the appearance is as if the peridotite was a

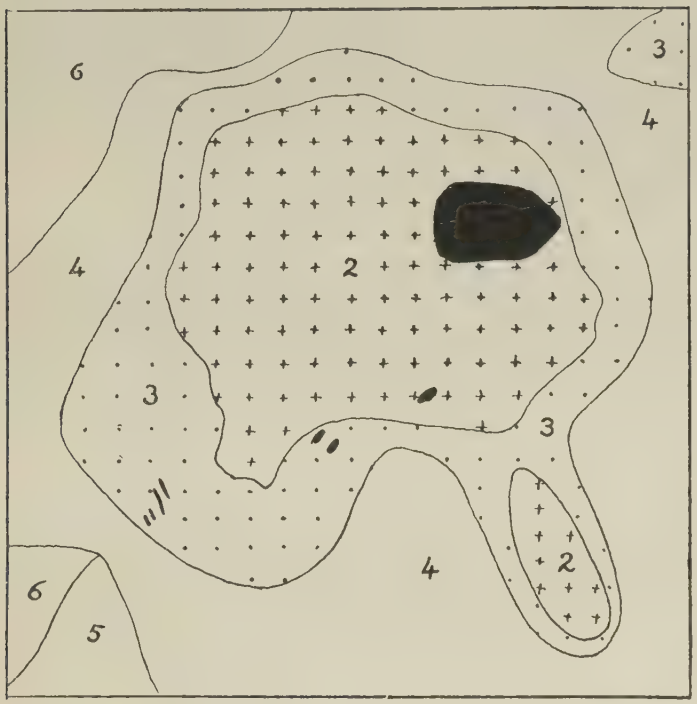

FIG. 28. Geological plan of the olivine rocks of Koniakowsky Hill, district of Nicolai-Pawda, Russia; after Duparc and Grosset. Black, dunite; 2, pyroxenic peridotites; 3, melanocratic olivine-gabbro; 4, normal olivine gabbro; 5, norite; 6, diabase. Scale, 1 : 100,000.

younger, stock-like mass which was intruded after the consolidation of the diorite " (or gabbro).

In support of the view expressed by Duparc, we may note that at Susimäki, Finland, M. K. Palmunen has described a hornblende-gabbro which passes centrally into a peridotite composed of olivine, hornblende, pyroxene and ore, and this again

into an ore-bearing dunite containing 60 per cent. of olivine and 36 per cent. of iron ore. An occurrence similar to this has long been known at Taberg, Sweden.

Coming now to rocks in which felspar plays a smaller part, there is the remarkable intrusion known as the Great Dyke in Southern Rhodesia. The outcrop is more than three hundred miles long, with an average width of about five miles, so the form is that of a sheet, whether vertical or inclined. But the various rocks which make up the sheet are not arranged parallel to its walls; they are described by B. Lightfoot as forming " a series of large discontinuous cakes, each of which has a gentle synclinal structure." The rocks include norite, pyroxenite, harzburgite and serpentinised peridotite, sometimes one, sometimes another predominating in the outcrop of the Dyke. (*Fig.* 29.)

The Great Serpentine Belt of New South Wales has many characters in common with the Great Dyke of Rhodesia. This is a body of olivine rocks and serpentine which has been intruded along the plane of a powerful reversed fault (W. N. Benson). The outcrop is not continuous, but many intrusive bodies from a hundred yards to thirty miles long crop out at intervals along the fault line, through a total distance of nearly two hundred miles. The width of the intrusion varies from a few inches to nearly two miles. There is no doubt that all these detached outcrops are connected underground, so that the whole is essentially one great dyke. The dominant rock is harzburgite (olivine-enstatite rock), but this passes locally into olivine-rock and enstatite rock, while the addition of a clino-pyroxene gives rise to a peridotite of the Lherz type. Amphibolite, olivine-gabbro, and anorthosite play a minor part in the complex. All the magnesian rocks are more or less serpentinised. Garnet-prehnite rocks are developed locally; they are probably altered lime-gabbros.

In the Dun Mountain subdivision of Nelson, New Zealand, peridotites and serpentines form a belt about twenty miles long and from half a mile to three miles wide, following the strike of the highly tilted Maitai series (Trias-Jura). In the west this belt runs parallel to a zone of limestone, quarter to half a mile broad, from which it is separated by a marginal zone of diabase; elsewhere the contact rocks are argillaceous. The greater part of the intrusion is serpentine, but dunite (pure olivine rock) and harzburgite (olivine-enstatite rock) are also preserved in the fresh state. There are many dykes of a grossularite-diallage rock

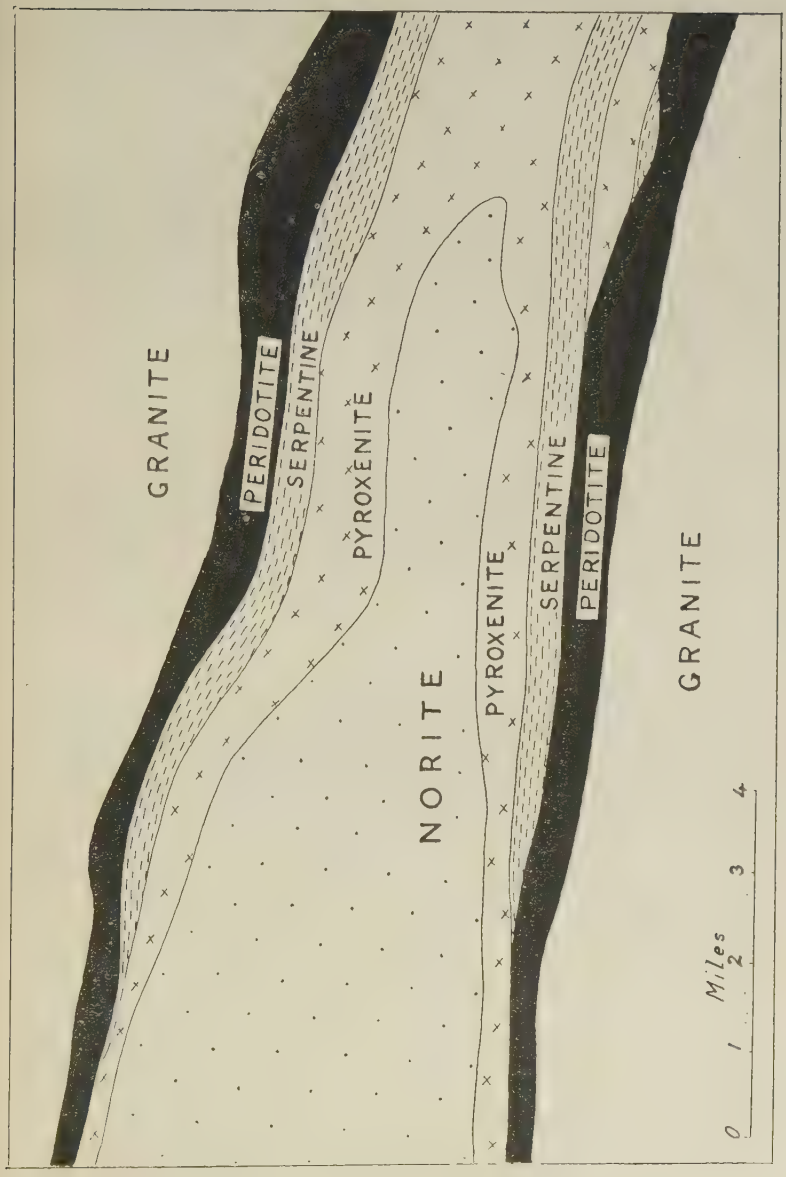

FIG. 29. Plan of a portion of the Great Dyke of Rhodesia. (After B. Lightfoot.)

which has been called " rodingite," and a belt of this rock extends for five miles parallel to the main intrusion and about quarter of a mile away from it. The dunite is the most magnesian rock known (MgO up to 47 per cent.), and the rodingite the richest in lime (CaO up to 32 per cent.). These rocks were mapped and described by Bell, Clarke and Marshall. (*Fig.* 30.)

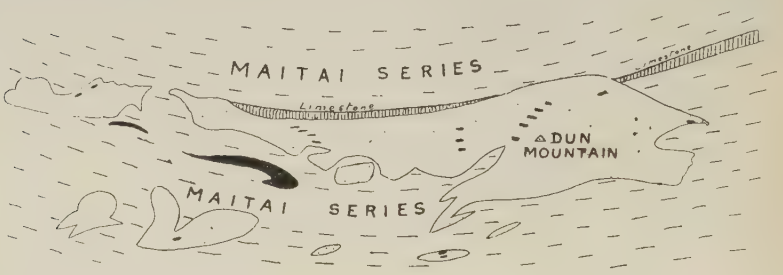

FIG. 30. The peridotite intrusions of Dun Mtn., New Zealand. (After Bell, Clarke and Marshall.) The surrounding rocks are shales and greywackes of the Maitai Series (Trias-Jura), with a thick limestone, from which the peridotite is separated by a marginal zone of diabase. Black areas are rodingite (grossularite-diallage rock). Scale, 4 miles to 1 inch.

In another characteristic type of intrusion, the olivine rock occupies more or less vertical pipes, which apparently represent the throats of former volcanoes. The best known examples are the " kimberlite " pipes of South and Central Africa. One of the largest of these pipes, the Premier Diamond Mine, near Pretoria, is 2,800 feet in greatest diameter. P. A. Wagner states that in section, every pipe has the form of a more or less symmetrical, steep-sided funnel, there being a steady shrinkage in size with increasing depth. Although a connection between individual pipes is not often apparent at the surface, yet mining operations have revealed that in many cases the pipes are arranged along dykes, being sometimes mere enlargements or " blows " in the course of the dyke, while in other cases they represent points where an old channel of eruption, marked by a dyke, has been re-opened during a younger phase of explosive volcanic activity. The Newlands Diamond Mine, for example, consists of four small pipes arranged along a narrow dyke; the Voorspoed mine was discovered by following up a dyke; and the linear arrangement of the pipes in the Belgian Congo is apparent on Wagner's map.

The typical rock of the pipes, the " blue ground " or kimberlite, is a serpentinised peridotite, which originally consisted to the extent of half or even three-quarters of olivine.

Summarising these observations regarding the geological occurrence of olivine rocks, we observe that the following types are represented :—

(a) Bodies of fairly uniform composition, olivine being a relatively minor constituent of a felspathic gabbro or norite.

(b) Approximately horizontal sheets, showing a concentration of olivine in one or more layers towards the base, with felspathic rocks above.

(c) Cores of olivine-rich rock within large bodies of olivine-poor or olivine-free gabbro.

(d) Inclined or vertical sheets (dykes) of peridotite and serpentine, differentiated either vertically, laterally, or irregularly.

(e) Dykes and pipes containing one type of peridotite throughout, with no significant differentiation.

(f) Surface flows of olivine-basalt, the effusive form of olivine-gabbro.

From cases (a) and (f) we must conclude that, so far as the upper crust of the earth is concerned, the olivine-gabbro type of magma is a primary one; that is, it is not within our knowledge derived from any other type of magma. On the other hand, cases (b) and (c) suggest that many olivine-rich rocks have been formed by the sinking of early-formed olivine crystals out of a large body of magma, which contained enough silica to have transformed all the olivine into pyroxene if the separation had not taken place; that is, these olivine rocks may have been derived from a saturated gabbro-magma. But cases (d) and (e), again, seem to require the existence of primary peridotitic magma, especially to account for the occurrence of kimberlite of almost precisely similar character in pipes which are scattered through forty degrees of latitude on the continent of Africa.

The view has been advanced that peridotites may be developed in consequence of the assimilation of magnesian limestone by granitic magma. Among the products of reaction between granite and limestone in the Pyrenees, A. Lacroix describes a complete series of rocks ranging in composition from hornblende granite to hornblende peridotite; the last a rock consisting of

large crystals of hornblende which enclose numerous rounded or irregular grains of olivine, closely resembling the well known peridotite of Schriesheim, Germany. (*Fig.* 9, page 64.) Whatever the facts may be in the Pyrenees, there can be no suggestion of such an origin in the case of any of the larger peridotite intrusions. The dunite of Dun Mountain, for example, runs parallel to a thick belt of limestone for fifteen miles, but the olivine rocks are separated by diabase from the limestone. The Serpentine Belt of New South Wales traverses a series of ancient sediments which include limestones, but there is nothing to suggest any connection between the presence of limestone and the composition of the eruptive rocks. The kimberlite pipes of Africa are on the whole scarcer in limestone areas than elsewhere.

W. N. Benson has pointed out that if peridotites were formed in the way Lacroix describes, it would be difficult to account for the relatively high proportions of nickel and chromium oxides which they contain, for these oxides are almost never found either in granite or in limestone. We may conclude, then, that peridotites are not generally due to any chemical reaction taking place in the known regions of the crust and that peridotite magma is " primary " in the same sense as granitic magma; but that there is also a definite group of peridotites which have been formed in consequence of the sinking of olivine and pyroxene crystals out of gabbro magma.

The Geology of Nepheline Rocks. Nepheline rocks are much scarcer than those that contain olivine, and most of the occurrences are of quite small dimensions. The complex of soda-rich rocks in the Kola Peninsula (Umptek and Lujaur-Urt) occupies some six hundred square miles; it has not been mapped in detail, but if all the rocks are undersaturated then this is, as regards area, by far the largest known body of nepheline rocks. It is interpreted by W. Ramsay as a thick sheet or laccolite; the floor, of ancient crystalline rocks, is partly visible, but the roof, which is supposed to have been sedimentary, has been removed by erosion, leaving only some small, highly metamorphosed remnants.

The alkaline rock complex of South Greenland (Ivigtut, Ilimausak, and Igaliko) includes large bodies of peralkaline granite and syenite as well as nepheline rocks. This region, like Kola, has not been mapped in detail, and the large Igaliko mass is little known, because it lies beneath the edge of the great ice

cap; so no precise estimate of the mass of the nepheline rocks can be made. From N. V. Ussing's maps, it appears that the Ilmausak batholith contains some fifty square miles of nepheline rocks, and the Igaliko batholith perhaps a similar area, with an unknown extension beneath the inland ice-sheet.

The largest body of nepheline rocks that is known in detail is found in the group of hills known as Pilansberg (Pilaan's Berg) in the western Transvaal. Nearly the whole area of two hundred square miles covered by the Berg is constituted of rocks rich in nepheline, with only a small proportion of nepheline-poor or nepheline-free syenite. From certain structural features, this intrusion is judged to have the form of a stock, at least in its upper part, so its vertical dimension may be much greater than that of the Kola intrusion (W. A. Humphrey, H. A. Brouwer).

No other area is known which comes near the dimensions of these three. The Ditró stock in Transylvania has an area of approximately fifty-six square miles, according to F. Berwerth, but the exposures are poor and the structure is not properly known. The Serra de Monchique stock, in Portugal, covers about twenty-four square miles; Fourche Mountain, Arkansas, about fifteen; and the Bancroft intrusion, in Ontario, about ten square miles. The nepheline rocks of the Christiania district, Norway, which bulk so largely in petrographic literature, do not cover more than ten square miles in all.

The various intrusion-forms of nepheline rocks may be summarised as follows:—

(a) Local developments of granite batholiths.
(b) Independent stocks and laccolites.
(c) Volcanic plugs.
(d) Sheets and dykes, mostly of small size.

Nepheline-bearing lavas (phonolites, nepheline-basalts) are among the less common types of lava, and their bulk is quite insignificant compared to that of the rhyolites, dacites or basalts.

In view of the comparatively small size of most of these intrusions and extrusions, and the very frequent association of nepheline rocks with syenites and granites, into which they appear to pass by gradual transition, it is likely that no great reservoirs of primary alkaline magma exist beneath the lithosphere, and that where nepheline-bearing rocks occur, they are due to special physical or chemical conditions which have affected granitic or basaltic magma in the upper crust.

Other observations that seem especially significant, as regards the origin of nepheline rocks, are

(1) their very frequent occurrence in association with thick limestone formations; and

(2) their richness in such uncommon elements as fluorine, chlorine, phosphorus, zirconium, titanium, and the cerium-yttrium group of metals.

The second point has been emphasised especially by C. H. Smyth, who points out that the elements with which the alkaline rocks are enriched are the very ones which are characteristic of pegmatite veins. As the segregation of pegmatite is generally believed to have been accomplished by the agency of water and other volatile compounds of low molecular weight (the so-called "mineralising agents"), Smyth contends that the simultaneous concentration of rare elements and alkalies, in the nepheline-bearing rocks, must be due to the same agents. In particular he thinks that "water above the critical temperature, or even, at some stages, dissociated, was a large, if not the largest factor." Smyth's contention is almost certainly correct, so far as it goes, but it fails to account for the deficiency of silica, which has caused nepheline to appear in place of the usual albite and quartz of pegmatite veins.

R. A. Daly lays stress on point (1), and maintains that all alkaline magma has been produced from basaltic magma by reaction with limestone. He supposes that some of the silica, which would normally have entered felspar molecules, combined instead with lime, and that the heavy lime-silicates so formed sank to the bottom of the magma reservoir, leaving the upper part of the magma impoverished as regards silica. Daly also ascribes a part to the escaping carbonic acid, and to magmatic gases, in carrying alkalies towards the top of the reservoir. The magma is supposed to become differentiated, by this double agency, into a lower, pyroxenic portion and an upper, alkaline portion, from which, by further differentiation, all possible types of alkaline rock may be derived.

Except as regards the nature of the primitive magma, Daly's theory finds an impressive amount of support in the field. Some of the evidence has already been cited in Chapter IV., but we must now look further into the matter.

The nepheline rocks of Ontario, according to Adams and Barlow, are invariably found either at the junction between granite and limestone, or else in the limestone itself near the

granite margin. (*Fig.* 31.) The transition from granite through syenite into foyaite can be followed in the field, when one observes first the gradual disappearance of quartz, then the increase of albite at the expense of potash-felspar, and concurrently an increase in the proportion of dark minerals, then the appearance and increase of nepheline in the rock. In the limestone, crystals of nepheline, biotite and other silicates are developed all along the margin of the nepheline-bearing rock, while masses of

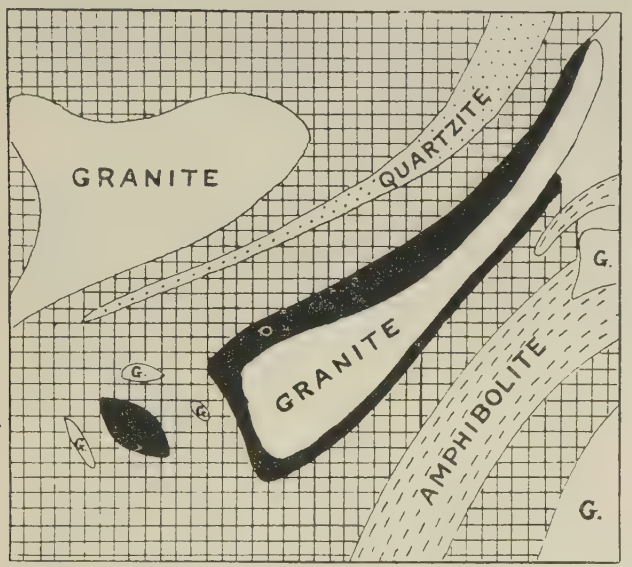

FIG. 31. Map of part of the Monmouth district, Ontario, showing the relation of foyaite (black) to granite (white) and limestone (squared). Scale, one inch = two miles. (After Adams and Barlow.)

limestone, enclosed in the nepheline rock, are seen in various stages of replacement by the magma. At Tory Hill, W. G. Foye has described a laccolitic body of the nepheline rock which rests on a limestone floor. The rocks of the laccolite vary from a leucocratic felspar-nepheline pegmatite (specific gravity 2.674) at the top, through varieties which become steadily richer in pyroxene, garnet, hornblende, scapolite and calcite, to a garnet-pyroxenite (specific gravity 3.383) in contact with the limestone floor.

FIG. 32. Two sections through the laccolite of Loch Borolan, Scotland. (S. J. S.) Scale, 1½ inches = 1 mile.
i, subacid granite, average content of lime 1 to 1.5 per cent.
ii, syenite, average content of lime 2 to 3 per cent.
iii, diopside, melanite and nepheline rocks, average content of lime 8 to 14 per cent.
iv (black), melanite pyroxenite, content of lime 22 per cent.
v (dotted), Cambrian limestone.

At Loch Borolan, in north-west Scotland, there is a somewhat similar laccolitic intrusion with a limestone floor. The upper layers of the rock are of granite, passing down into quartz-bearing syenite, then into quartz-free syenite, melanite syenite, and melanite-nepheline syenite, while the only rock which is seen in actual contact with the limestone is a melanite-pyroxenite containing 22 per cent. of lime (S. J. S.). (*Fig.* 32.) J. J. H. Teall wrote that "the evidence available suggests that the quartz-syenites shade into the quartzless syenites, and these again into nepheline syenites."

The laccolitic intrusion of Ice River, British Columbia, is entirely surrounded by limestone and calcareous shales. The rocks of the laccolite are rich in nepheline, and towards the sides and floor of the intrusion they become more and more melanocratic, acquiring a high content of pyroxene, iron ore, apatite, sphene, and lime-garnet. J. A. Allan shows that in rising to its present position the magma had to break through at least ten thousand feet of calcareous rocks.

At Jacupiranga, Brazil, a body of variable nepheline rocks, including very melanocratic types, is intrusive in a series of slates and schists with characteristic and persistent limestones, and a mass of limestone forms a ridge in the heart of the eruptive area (O. A. Derby). The Ditró stock, in Transylvania, is also intrusive in schists with strong limestone bands, which give rise to limestone escarpments on the north-east, east, and south-east sides (F. Berwerth).

In the district of Sekukuniland, Transvaal, a stock of nepheline rocks, having an area of more than six square miles, is entirely surrounded by granite, but it encloses a great block of limestone nearly half a mile square. At a distance from the limestone, the rock contains soda-potash felspar, nepheline and ægirine chiefly, but with approach to the limestone the felspar diminishes, while nepheline increases, the pyroxene becomes rich in lime, and cancrinite, apatite, melanite, sphene and calcite all appear as minor constituents of the rock. Comparison of chemical analyses of the two extreme types show that the magma in the neighbourhood of the limestone has lost fourteen per cent. of silica and three per cent. of ferric oxide, while it has gained ten per cent. of lime, two of magnesia, three of phosphoric acid, and one of carbonic acid; the proportion of nepheline rising meanwhile from twenty-seven to fifty-two per cent. (S. J. S.). (*Figs.* 33, 34.)

The geological relations of the little stock of nepheline rocks in the Fen district of Norway are almost identical with those of the Sekukuniland stock; but the stock is much smaller, the enclosed block of limestone relatively much larger, and the effects of assimilation of limestone are seen in all the rocks developed, which are melanocratic rocks rich in lime-silicates and nepheline. The geology and petrology of this stock have been worked out in great detail by W. C. Brögger.

FIG. 33. Plan of foyaite stock cutting granite; Sekukuniland, South Africa. The black area is an enclosed mass of limestone, measuring 1 mile × ¾ mile, about which the foyaite has been changed into an ijolite rich in lime (dotted area).

The complex of Magnet Cove, Arkansas, is similar in type to the last two. It occupies an elliptical area of some five square miles, within which the rocks have a roughly concentric arrangement. Both nepheline and leucite are or were developed in these rocks, which show an increasing proportion of magnesia and lime towards the centre of the area, where several masses of contact altered limestone have been found (J. F. Williams). The outcrops in the centre of the Cove are largely obscured by alluvium, which possibly explains why little attention has been paid to the part which the limestone may have played in determining the character of the eruptive rocks.

The Kaiserstuhl, in Baden, presents another case of the same kind, which has been less deeply eroded than the above examples, consequently the rocks are mainly lavas and breccias. In the nepheline and leucite basalts of this plug, inclusions of more or less altered limestone are commonly found, as well as lumps of melanite, enclosing nepheline and apatite, which are probably completely altered limestone enclosures. In the centre of the complex is a great mass of metamorphosed limestone, measuring nearly a square mile (F. Graeff).

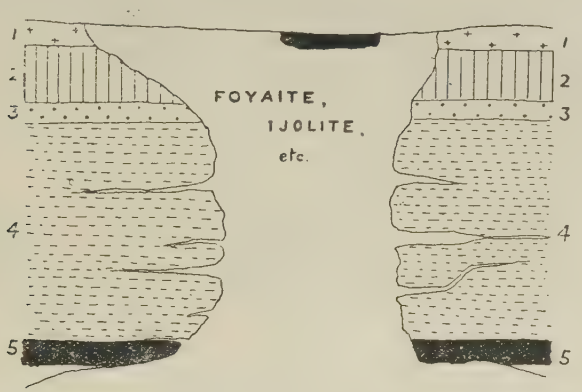

FIG. 34. A hypothetical section through the Sekukuniland foyaite stock, showing the source of the great limestone enclosure. 1, granite; 2, norite; 3, quartzite; 4, Pretoria series; 5 (black), limestone. Vertical and horizontal scales approximately the same.

Another area which is remarkable for the intimate association of nepheline-rich rocks with carbonates is the island of Alnö, Sweden, which has been described by A. G. Högbom. A good account has also been given, in English, by R. Workman. In this case we have once more to do with a stock of less than ten square miles, consisting of rocks rich in nepheline, intruded into a region of almost limeless granitic gneiss. There is no single great enclosure of limestone, as in all the above instances, but the nepheline rocks are charged through and through with calcite, which is present in masses of all sizes, from bodies of very pure crystalline limestone one or two hundred yards long, down to minute crystals intergrown with the silicates of the eruptive rock. (*Fig.* 35.)

Much has been made of the Alnö stock by petrologists who

are opposed to the idea of reaction between magma and sedimentary rocks. They point out that no limestone formation occurs for a great distance around Alnö, and that the enclosed crystalline carbonate masses have no resemblance to the rather impure Silurian limestone of Sweden. They offer the alternative view that the crystalline limestone is itself of magmatic origin; yet it should only be necessary to study the series of occurrences,

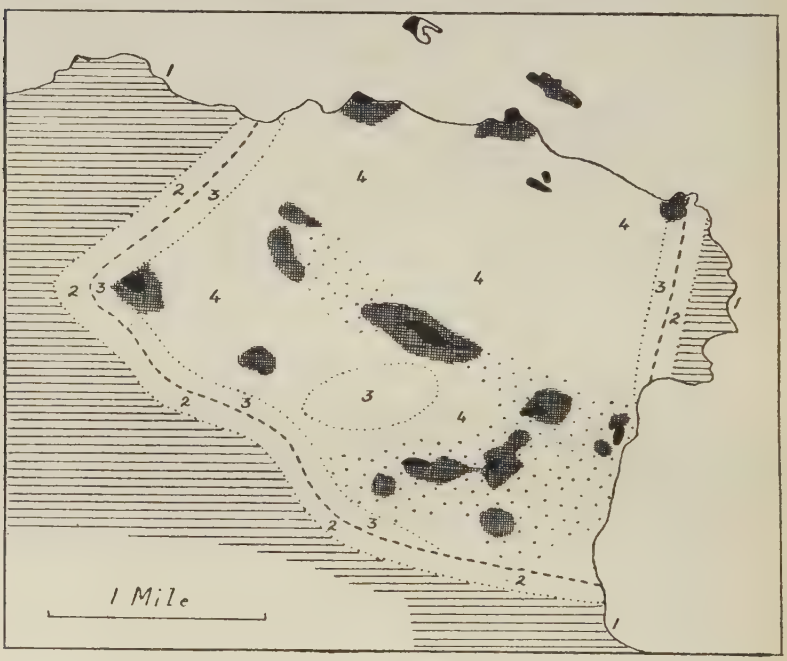

FIG. 35. Geological plan of the nepheline rocks on the island of Alnö, Sweden. (After A. G. Högbom.)

1, gneiss; 2, quartz-free border of gneiss; 3, acidified margin of nepheline rocks; 4, nepheline rocks (foyaite, ijolite, etc.); dotted areas, nepheline rocks containing much calcite; cross-hatched areas, nepheline rocks intermingled with limestone; black areas, relatively pure limestone.

Ontario-Jacupiranga-Sekukuniland-Kaiserstuhl-Fen-Alnö, to see how gratuitous the assumption of a carbonate magma is, quite apart from the physical and chemical difficulties which it raises. In Ontario we have a nephelinic magma breaking through an undoubtedly sedimentary limestone by stoping and solution; at Jacupiranga a great block has been removed from the limestone walls and carried out to the middle of the stock; in Sekukuniland

the formation from which the enclosure was derived is several miles underground; at Kaiserstuhl too the limestone block has been brought up from a deeply buried sedimentary formation. In the Fen district the source of the limestone is still more problematic; and in addition we observe, in the last two areas, an increasing degree of intermingling of limestone with eruptive rock. Finally, at Alnö, the limestone is highly disintegrated and has been completely recrystallised in the magma. Why, then, invoke a hypothetical carbonate magma, instead of following the

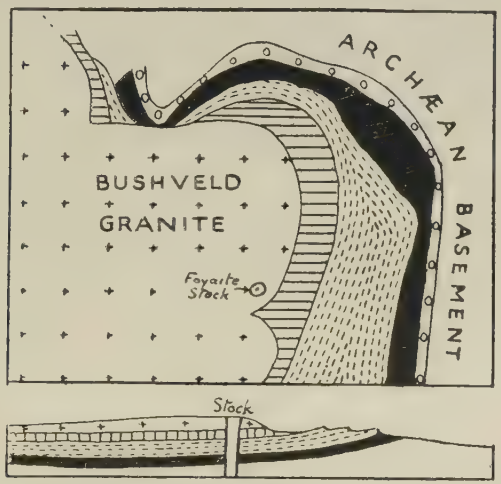

FIG. 36. Map and section of part of the Bushveld Complex, Transvaal, showing the position of the Sekukuniland foyaite stock in relation to the limestone (black). The nearest outcrop of the limestone is fifty-five miles distant from the stock.

argument from its beginning, in Ontario, to its logical end, in Alnö?

The difficulty of finding a sedimentary source for the limestone at Alnö has been exaggerated. The arguments based on the purity of the crystalline carbonates, the absence of bedding planes, absence of fossils, and so on, were all brought forward half a century earlier in regard to the limestone of the Kaiserstuhl, and they have been satisfactorily answered by F. Graeff. In a word, these features are the natural consequence of the intense metamorphism and recrystallisation which the limestone underwent when it was saturated with hot magmatic fluids. As for the

absence of any limestone formation from the neighbourhood of Alnö, it is perhaps not absurd to draw an imaginary parallel to the case. Suppose that the Transvaal were as deeply submerged as South Sweden is. The Sekukuniland stock would then be situated in a large island of red granite, which would infallibly be interpreted as the top of a huge batholith, and the possibility of a thick limestone formation lying several miles beneath the granite would not be dreamt of. Yet that explanation happens to be the correct one, as the geological map of the Transvaal shows. (*Fig.* 36.) But without looking underground at all, there are limestones enough in Sweden and Norway to account for everything that has been observed at Alnö and in the Fen district.

Summing up, we see that a remarkable number of bodies of nepheline rock show an intimate connection with limestone, with which the magma has undoubtedly reacted to a greater or less extent. In other cases, where limestone is not actually to be seen

FIG. 37. Cross-section through Granitberg, South-West Africa, to illustrate the approaching disappearance of the limestone (black) into which the foyaite was intruded. (After E. Kaiser and W. Beetz.)

in the country rocks, it is positively known either to underlie the complex as in Pilansberg, Sekukuniland and the Kaiserstuhl, or to have been present in the original sedimentary cover of the area, since removed by erosion. The last is the case at Granitberg, in South West Africa. Quite a short period of geological time will suffice for the removal of the last traces of the Nama limestone from the neighbourhood of Granitberg, after which that considerable body of nepheline rocks will appear to rise out of a floor of ancient schists, with no limestone anywhere near it, just as is now the case in Greenland and the Kola Peninsula. (*Fig.* 37.)

We conclude, then, that nepheline rocks are seldom, if ever, formed from a primary magma of their own composition; the nepheline magma seems to be, with great probability, a secondary magma produced in most cases from granitic, but sometimes from basaltic, magma in consequence of the operation of a special,

local factor; and a very strong case can be made out for the belief that this factor has been a reaction or interchange of constituents with limestone, as R. A. Daly has long maintained.

As regards *sodalite, haüyne, nosean* and *cancrinite,* in view of the close relationship between these minerals and nepheline, and especially in view of their almost invariable association with nepheline in eruptive rocks, it seems unnecessary to discuss their occurrence apart from that of nepheline. They are most simply regarded as additional products of nepheline, containing a chloride, a sulphate, and a carbonate radicle respectively.

The case of *analcime* is different, for this mineral contains twice as much silica as nepheline does. Analcime is associated with nepheline in many rocks, but it also makes its appearance independently of nepheline, in dyke-rocks which are usually of a rather melanocratic type. Among these are the monchiquites, a group of dark, compact dyke-rocks which consist very largely of augite and olivine, with or without a little hornblende or biotite, set in an isotropic base which has the composition and properties of analcime. The fourchites are similar rocks which lack olivine. Monchiquites and fourchites are characteristically developed in the neighbourhood of intrusions of nepheline rocks, but they do not as a rule contain any nepheline.

The names teschenite and analcime-dolerite (analcite-diabase in America) are applied to a group of dyke-rocks which in most respects resemble dolerites and olivine-dolerites respectively, but differ from these by the presence of interstitial analcime. It is not possible to establish any generalisations regarding the occurrence of these rocks, which form minor intrusions in many parts of the world. The magma which gave rise to them was clearly undersaturated with silica, and it was also highly charged with water, for some of these rocks contain nearly fifty per cent. of analcime, which itself holds 14 per cent. of water.

It remains to be discovered what condition it is that determines the production of nepheline in one rock and analcime in another.

The Geology of Leucite Rocks. Only one locality is known at present, where unaltered leucite occurs in a major intrusion, namely the Highwood Mountains of Montana, where the rock which Weed and Pirsson called " missourite " forms a stock measuring two and a half miles by half a mile; it is intrusive in

shale and tuff. All other leucite rocks form lava flows or dykes of insignificant size, and consequently it is difficult to reach any conclusion, by observation in the field, regarding the cause of the deficiency of silica which leads to the production of leucite.

There seems to be only one clear case of direct association between unaltered leucite and limestone. J. F. Kemp described a dyke-rock which cuts limestone near Hamburg, New Jersey, and which contains white spheroids, rising to a centimetre in diameter, in a matrix of biotite, augite and analcime. These spheroids are also composed of analcime, but in a limestone quarry three miles away, a completely similar dyke was found, in which the spheroids showed the typical twinning of leucite and gave a strong potash reaction. It is therefore considered that leucite was the original mineral in both cases. No conclusion whatever can be based on a solitary instance such as this, but in view of the almost invariable occurrence of nepheline in association with leucite, and of the strong evidence that connects limestone with the genesis of nepheline, we cannot avoid the suspicion that the formation of leucite is also a consequence of the reactions postulated by R. A. Daly.

The Geological Occurrence of Rocks Containing Unsaturated Lime Minerals. For *melilite*, as for nepheline, there is a considerable volume of evidence which connects it with limestone. The very instances which supply the strongest evidence in the case of nepheline, sometimes do so for melilite too; thus at Alnö there are many dykes of melilite-basalt and "alnöite" (a biotite-melilite-basalt) in the limestone and in the gneiss. In the neighbourhood of Montreal, Canada, there are not only striking examples of nepheline rocks in direct contact with limestone, but also plugs and dykes of alnöite cutting limestone. J. Stansfield has described remarkable rocks containing melilite, haüyne, and biotite, with or without nepheline, which invade limestone in the Oka Hills, Quebec; he insists on the assimilation of lime as a condition of their formation.

In the Polzen district of Bohemia, K. H. Scheumann has described many dykes of melilite-bearing rocks, in the formation of which he claims that assimilation of lime has taken part. E. Becker has studied the distribution of melilite basalts in the south-west of Germany, and finds that they are restricted to regions where thick limestones are present.

N. L. Bowen has found that melts of nepheline and diopside,

in the crucible, give olivine and melilite at temperatures between 1100° and 1300°. He advances this as evidence that melilite and certain other lime-rich minerals are "not necessarily an indication of contamination of the magma by limestone." But if the nepheline-diopside magmas in nature are themselves products of the assimilation of limestone, as we have seen reason to suppose, then Bowen's contention loses its force.

On the other hand, there are occurrences of melilite, just as there are occurrences of nepheline, in places where no limestone is found. In the Sutherland district of South Africa, Rogers and Du Toit have described a number of pipes of melilite basalt that cut shales and sandstones of the Beaufort series. It is especially remarked that the Beaufort beds "do not contain much calcareous matter"; nevertheless the melilite basalt holds crystals of calcite, which behaves as if it were a primary constituent of the rock. Rogers has also described pipes of melilite-nepheline basalt cutting gneiss in Namaqualand, with no known limestone near at hand. C. S. Ross has lately found an alnöite in Montana, remote from any known limestone.

For the *lime-iron garnet* (melanite or andradite), the evidence is still more complete that it is a product of assimilation of limestone. It may almost be stated as a law, that wherever a syenitic rock is seen in intimate contact with limestone, there a lime-garnet will be present; and further that wherever in the world a syenitic rock carries a lime-garnet, it will be found to make contact with limestone. Some of the most striking illustrations of this association are to be found at the following localities, to many of which we have already made some reference:—

Haliburton, Ontario; Mount Royal, Quebec; Oka Hills, Quebec; Ice River, B.C.; Franklin Camp, B.C.; Magnet Cove, Ark.; Potash Springs, Ark.; Gunnison Co., Colo.; Kuusamo, Finland; Alnö, Sweden; Fen district, Norway; Kaiserstuhl, Baden; Ditró, Transylvania; Cevadaes, Portugal; Pouzac, Pyrenees; Assynt, Scotland; Sviatoy Noss, Transbaikalia; Sekukuniland, Transvaal; Ambavatoby, Madagascar. Another admirable illustration of this point has lately been found by R. M. Craig in Nyassaland.

At several of these localities, melanite is found in the immediate neighbourhood of the limestone and *nowhere else;* and at Mount Royal, Quebec, a zone of brown garnet was found separating the limestone from the nepheline rocks.

A few other lime-rich minerals have been found in special cases, in such close and intimate relation to an invaded body of limestone that there is every reason to believe that assimilation of lime was the direct cause of their formation. Such are scapolite, recorded at Ile Cadieux, Quebec, and Craigmont, Ontario; monticellite, which has been found at Ile Cadieux and St. Hilaire Mountain, Quebec, at Magnet Cove, Arkansas, and at Alnö, Sweden; lime-olivine, observed in a solitary case in Tasmania; wollastonite and pectolite, one or other of which has been found in Arkansas, Sekukuniland, Pilansberg, Tasmania, Quebec, and other localities; and perovskite, which is a rare accessory constituent of many nepheline and melilite rocks, but an abundant one in Gunnison Co., Colorado. In nearly all these cases the association with limestone is so marked that the influence of assimilation can hardly be questioned, and, in addition, the lime-mineral is always associated with nepheline, or melilite, or both of these.

Vesuvianite has been found as a constituent of a nepheline rock at Almunge, Sweden (P. Quensel), where there is no visible limestone to account for it, but the rock carries primary calcite.

The Geology of Corundum Rocks. That some corundum may be developed in consequence of the assimilation of aluminous sediments by eruptive magma has been admitted by several writers. Thus K. Busz showed clearly that corundum had been formed in this way in certain dyke-rocks in Devonshire (see page 62), and H. H. Thomas has studied the various stages in the transformation of aluminous rock-fragments into anorthite-corundum-spinel aggregates, within dolerite sills on the island of Mull, Scotland. L. V. Pirsson assumed that the sapphires in the lamprophyre dyke at Yogo Gulch, Montana, were formed from the clay slates through which the dyke has broken, and the sporadic occurrence of sapphire in the basalts of the Rhineland has generally been explained in the same way. But it is not clear that any such explanation is applicable to the widespread occurrence of corundum in Canada and South Africa, in particular.

Corundum is found in small quantity in some of the syenites and nepheline rocks of Ontario, but it is especially abundant in the syenite-pegmatites, which form veins and dykes sometimes as much as eighteen feet wide. These very coarse-grained pegmatites are made up of pink, perthitic felspar (soda-orthoclase)

with corundum and a little biotite, muscovite, calcite, and exceptionally a very small amount of quartz. Corundum may make up as much as thirty-five per cent. of this rock. The felspar is not always an alkaline one, but varies from microperthite through albite, oligoclase and andesine to bytownite. A. E. Barlow particularly emphasizes the point that "the nepheline and related alkaline syenites with which the principal occurrences of corundum are associated, show an extreme and rapid variation in composition," although they form a single geological unit.

The important corundum reefs of the Transvaal are coarse pegmatites, which carry quartz and mica when they cut granite, and only become corundum-bearing when they enter a region of basic magnesian rocks (serpentines, pyroxenites, etc.). The reefs then consist of plagioclase (oligoclase or andesine) with corundum and biotite; orthoclase is rare; and A. L. Hall remarks that "not a single example was observed where a corundiferous rock also carried quartz." The surrounding rocks have their magnesian constituents changed into talc in the neighbourhood of such a reef, indicating an addition of silica.

The conditions in North Carolina, Georgia, Massachusetts, and in Plumas Co., California, are almost identical with those in the Transvaal. In each case the mineral occurs in pegmatite veins about the junction between granite and a magnesian rock which is generally some variety of peridotite.

At Kyschtym, in the Ural Mountains, similar conditions recur; in this instance a large dyke of anorthite-corundum-biotite rock intervenes between granite and serpentine. In the same district there are also stock-like bodies of corundum syenite in the granite; in these the felspar is microperthite, and J. Morozewicz notes that a few grains of quartz are very rarely to be seen. This locality is in the neighbourhood of Miask, where nepheline rocks have long been known to occur, so there would seem to be a close general resemblance between the corundum rocks of the Ural and those of Ontario.

In India, the corundum-bearing rock at Coimbatore, Madras, is once more a pegmatite, having microperthite and biotite as its silicate constituents. The geological relations are obscured by surface deposits, but T. H. Holland shows that the distribution of corundum is definitely related to outcrops of nepheline syenite.

In brief, the typical corundum-bearing rock in all parts of the world is a more or less coarse-grained pegmatite, which is typically associated either with nepheline rocks or with basic

magnesian rocks. In the former case the corundum rock is connected with the nepheline rock by gradual transition, and sometimes holds a little nepheline; thus one can hardly fail to suspect that the appearance of corundum is connected with the desilicating reaction which produced the nepheline. In the latter case the corundum rock is intrusive in the magnesian rock, and there is positive evidence, in the Transvaal and elsewhere, that the country rock has gained silica from the magma which gave rise to the corundum pegmatite. Thus it seems to be established, by the evidence of field geology, that corundum-bearing rocks are produced, either directly or indirectly, in consequence of reaction between granitic magma and its walls.

The Mineralogy of the Undersaturated Rocks. Quartz is excluded from these rocks, by definition; yet it is necessary to make allowance for the exceptional type of rock in which, as a consequence of rapid cooling or imperfect mixing, an unsaturated mineral is present together with a little quartz or siliceous glass. In a eucrystalline rock, such a residue of silica generally forms micropegmatite in the interstices; in a hypocrystalline one, the silica remains in the glassy base, and can only be detected by chemical analysis. We have already noticed some cases of the preservation of olivine crystals in a siliceous base (pages 203, 211). In order to ascertain whether such a rock is actually oversaturated, saturated, or undersaturated, one must determine and compare the proportions of olivine and of quartz or excess silica. Roughly speaking, two volumes of olivine will combine with one of quartz to form enstatite; if there is more olivine than this, then the rock is to be considered undersaturated in spite of the actual presence of quartz.

It is possible for a similar state of unstable equilibrium to be exhibited by a leucite rock, for we have seen that orthoclase splits up into leucite and silica about 1170°. If a potassic magma began to crystallise above that temperature and were then chilled rapidly, we should expect to find leucite crystals preserved in a siliceous base. A leucite-rich lava from Wyoming, which was described by W. Cross, has a groundmass of leucite crystals, cemented together by a colourless glass which contains enough silica to have transformed the whole of the leucite into orthoclase.

Among the felspars in undersaturated rocks, strongly potassic varieties are rare. The felspar of the nepheline rocks is soda-orthoclase, microperthite, or soda-rich plagioclase; that of the

leucite and olivine rocks is typically richer in lime than soda, ranging from labradorite to practically pure anorthite.

Leucite is more commonly associated with plagioclase than with orthoclase. The reason may be that if much soda is present in the magma, the available silica is distributed between soda and potash, but the unsaturated potash molecules (kaliophilite) are taken into solid solution by the more abundant soda molecules, forming ordinary "nepheline," which generally contains about one-fourth to one-sixth of its weight of kaliophilite; while if the magma contains much lime and relatively little soda, the unsaturated potash molecules are deprived of this shelter and are compelled to crystallise independently in the form of leucite.

The substance known as "pseudo-leucite" is something of a mystery. In many parts of the world there have been found, especially in dykes and small stocks, polygonal bodies preserving more or less sharply the outlines of the trapezohedron. These are not simple minerals, but aggregates of orthoclase and nepheline grains, sometimes with scapolite, mica, or zeolites in addition; they are obviously pseudomorphs, and they have usually been assumed to result from the breaking down of leucite crystals according to the approximate equation

$$2(K, Na)AlSi_2O_6 = KAlSi_3O_8 + NaAlSiO_4$$
(leucite) (orthoclase) (nepheline)

C. W. Knight described excellent pseudomorphs of this kind in a phonolite occurring in the Ogilvie Range, Yukon territory. The orthoclase was observed to be granular in the interior of the pseudomorph, but lath-shaped at the margin, the laths standing perpendicular to the faces of the trapezohedron. Two of these pseudomorphs were analysed and showed 8.5 per cent. of potash to 7.1 per cent. of soda.

The "pseudoleucite" of Magnet Cove, Arkansas, which was described by J. F. Williams, shows a different arrangement of the felspar crystals, which are tabular and lie parallel to the faces of the trapezohedron. This rock has a holocrystalline groundmass, and with diminution and disappearance of the pseudomorphs, the rock passes without any break into a normal nepheline syenite of almost identical chemical composition. The bulk analysis of the rock, including pseudomorphs, gives 8.5 per cent. of soda and 6.8 per cent. of potash.

A particularly remarkable example of "pseudoleucite" was recorded by E. Hussak, from Serra de Caldas, Brazil. The pseudomorphs have a narrow mantle of orthoclase laths, within which they consist of orthoclase and nepheline, with a little spinel, corundum and pyroxene. They lie in a matrix of orthoclase, quartz, and a little biotite or ægirine. Quartz is never found in the pseudomorphs, or nepheline in the groundmass. Hussak suggests that the rock has been formed by granitic magma invading and breaking up a leucitic lava. In another rock, Hussak found both large "pseudoleucites" of the usual sort and microscopic crystals of analcime; he concluded that both were pseudomorphs after leucite, but that the former type had been formed under intratelluric conditions and the latter by the action of water.

While there can be little doubt that some "pseudoleucite" really is what its name implies, it by no means follows that this is true of all of it. H. S. Washington has suggested that "pseudo-leucite is not a pseudomorph after original leucite, but that it represents a distinct soda-potash mineral, as yet unknown, which was not stable under the conditions following its period of crystallisation." It is not unlikely, in view of the high soda content of nearly all rocks containing so-called pseudo-leucite, that the original mineral was analcime.

Nepheline, when it is an abundant constituent of a rock, crystallises before the alkali felspars and sometimes before pyroxene too; but when it is scanty it tends to occupy the interstices between the felspar crystals, and is then difficult to detect without staining. Sodalite may crystallise either early or late, and either before or after nepheline; but haüyne and nosean are usually among the first silicates to form. Cancrinite is perhaps in most cases a late product, formed by the action of magmatic fluids on nepheline; but in other cases it is clearly of primary origin, for prisms of cancrinite are sometimes enclosed in the alkali-felspars.

Analcime is generally one of the last minerals to crystallise from the magma, and in certain dyke-rocks (monchiquites) it forms the base in which all the other minerals lie. Nevertheless, H. S. Washington found crystals of analcime, of relatively early formation, in basalts of Sardinia; and in a remarkable rock found at Blairmore, Alberta, there are insets of analcime measuring as much as an inch in diameter, set in a fine-grained groundmass of analcime and other silicates (J. D. MacKenzie). Washington

shows that such early-formed analcime crystals have sometimes been mistaken for leucite. N. V. Ussing has found analcime crystals 12 centimetres in diameter in alkaline rocks of South Greenland.

The dark minerals, in rocks containing nepheline, are typically soda-diopside and ægirine. Frequently the core of a pyroxene crystal is pure diopside, which gradually becomes more and more sodic towards the outside, until the outermost zone is pure ægirine. In such a case the cores of the crystals may have crystallised very early, yet the mantles may have been formed at such a late stage that they enclose grains of felspar or nepheline. Soda-amphiboles are sometimes primary minerals, but in many cases they can be proved to have developed by transformation of ægirine; thus a single crystal may be composed of ægirine within and arfvedsonite or riebeckite without. Orthopyroxene is never found in a nepheline-bearing rock. Biotite is the commonest dark mineral in the nepheline rocks of Ontario and India, but in all the major occurrences of nepheline rocks mica is either lacking or quite subordinate to pyroxene. Eudialyte, ænigmatite, astrophyllite, and other rare minerals which consort with nepheline, generally crystallise late, forming spongy plates which enclose all the other minerals of the rock.

The dark minerals of the olivine rocks are the ortho pyroxenes and either pale greenish augite or purple titanaugite. A dark, chestnut brown hornblende is not uncommon, and biotite may be present too, but neither of these minerals can be said to be characteristic of the group. Olivine itself crystallises, as a rule, before any other heavy silicate, and little crystals of olivine are often enclosed by large numbers in plates of pyroxene, hornblende or mica, giving rise to the appearance sometimes described as "lustre-mottling."

Olivine is seldom associated with a highly potassic felspar, the probable reason being that orthoclase reacts with olivine, giving hypersthene and biotite. In the few cases where olivine has been identified in an orthoclase-bearing rock, it is possible that the mineral was actually fayalite, or at least a variety of olivine holding a large proportion of the fayalite molecule. Even the soda-rich plagioclase felspars are seldom found in association with olivine, the characteristic felspar of the olivine rocks being labradorite, bytownite or anorthite. When anorthite is present in large amount, it may crystallise before olivine, but if olivine is in excess it precedes anorthite (A. Harker).

Melilite is scarcely ever found apart from olivine, and generally crystallises after it but before the light silicates. In the alnöite of Montreal, J. Stansfield found that the order of crystallisation was olivine, iron ore, perovskite, biotite, melilite, while in the Oka Hills it was apatite, ore, mica, perovskite, melilite, nepheline, haüyne.

Corundum, spinel and chromite are minerals of early crystallisation.

The Chemistry of the Undersaturated Rocks. Since pure albite contains 69 per cent. of silica, it is clear that no undersaturated rock can hold more than that proportion. Quite a number of phonolites and some foyaites have about 60 per cent. of silica. The proportion of silica falls rapidly as olivine, nepheline or melanite becomes abundant, dropping to about 40 per cent. in the nepheline-rich ijolites and as low as 35 per cent. in many melilite rocks. A melanite-pyroxenite from Assynt, Scotland, has only 33.5 per cent. of silica (Washington's Tables, p. 725), and a melilite basalt from Sutherland, S. Africa, only 31.2 per cent. (W. T., p. 727), but even these low values are further depressed when free oxides are present in the rocks. A magnetite-periodotite from Caribou, Colorado, has only 27.7 per cent. of silica (W. T., p. 743); another such rock from Rhode Island has 22.3 per cent. (W. T., p. 743), and the corundum-anorthosite of the Ural Mountains has in places as little as 16.8 per cent. of silica (W. T., p. 325).

Alumina reaches the very high value of 73 per cent. in the rock last mentioned, which carries some sixty per cent. of corundum. Leaving such abnormal rocks alone, we find from 20 to 28 per cent. of alumina in many nepheline rocks, one of the highest recorded proportions being 28.8 in an urtite from Finland (W. T., p. 585). The theoretical minimum for this constituent would be zero, in a pure olivine rock; the peridotite of Yale, British Columbia, contains only 0.3 per cent. of alumina (W. T., p. 739).

Ferric oxide amounts to 21.8 per cent. in the magnetite-peridotite of Caribou, Colorado, and might rise still higher in rocks of this type. The minimum is practically zero, as in many leucocratic nepheline rocks.

Ferrous oxide makes up 70 per cent. of theoretical fayalite (iron-olivine). The fayalite-rich peridotite of the Transvaal has been proved to hold over 35 per cent. of ferrous oxide, and this figure would have been still higher if no oxidation has taken place (P. A. Wagner). The minimum is again virtually zero.

Magnesia should reach 57 per cent. in pure forsterite (magnesian olivine), but as all the olivine in eruptive rocks contains more or less iron, the highest values recorded are 47.4 in the peridotite of Dun Mountain, New Zealand, and 48.6 in the peridotite of Corundum Hill, North Carolina (W. T., p. 739). Magnesia falls almost to zero in highly leucocratic nepheline rocks.

Lime reaches its highest proportion in rocks that carry much anorthite, melanite or melilite. It amounts to 21.9 per cent. in a melanite-pyroxenite from Scotland (W. T., p. 717), 27.2 per cent. in the melilite rock of Gunnison Co., Colorado (W. T., p. 725), and 29.4 per cent. in the diallage-garnet rock of Dun Mountain, New Zealand (W. T., p. 669). Scarcely any lime is present in many peridotites.

Soda reaches the very high value of 19.5 per cent. in a sodalite rock from Beloeil Mountain, Quebec (W. T., p. 321). The proportion in pure sodalite is 25.6. Proportions of 10 to 17 per cent. are usual in nepheline rocks. Soda falls virtually to zero in peridotites.

Potash forms nearly 18 per cent. of a highly leucitic lava ("italite") described by H. S. Washington from Mount Vesuvius. Pure leucite has 21.5 per cent. of potash. Quantities of 7 to 11 per cent. are usual in leucitic lavas, and the minimum is again reached in peridotites, many of which are absolutely without potash.

Oxides of cerium, columbium and zirconium are often detected in appreciable quantities in nepheline rocks, while nickel, chromium, and vanadium oxides are generally to be found in rocks that contain much olivine. As much as 4.9 per cent. of zirconia may be found in the remarkable eudialyte-nepheline rocks of Greenland (W. T., p. 703); the same rock contained 0.75 per cent. of fluorine and 0.51 per cent. of chlorine.

Titania reaches the utterly abnormal value of 24.7 per cent. in a rock rich in perovskite, from Gunnison Co., Colorado (W. T., p. 745); in nepheline-rich rocks titania not infrequently amounts to three or four per cent., but even the value of seven per cent., which is reached in a single instance in the Transvaal (W. T., p. 595) is quite abnormal. Baryta (BaO) is often detected in rocks that are rich in potash; one of the leucite rocks of Montana gave 0.49 per cent. of baryta (W. T., p. 671).

Oxide of chromium may reach quite high values in rocks that carry much chromite. P. A. Wagner records 3.2 per cent.

of this oxide in an enstatite-olivine rock from the Rustenberg district, Transvaal, besides accumulations of nearly pure chromite. Nickel oxide amounts to 0.75 per cent. in a melilite-basalt in Baden (W. T., p. 723). The perovskite rock which was mentioned above, in connection with titania, also carries 0.2 per cent. of vanadium oxide.

The Classification of the Undersaturated Rocks. Within this class we recognise two prime divisions, as follows :—

I. *Non-Alkaline Division* :

Only heavy minerals are unsaturated (olivine, corundum, melilite, etc.),

II. *Alkaline Division* :

(A) Only light minerals are unsaturated (nepheline, leucite, etc.),

(B) Both light and heavy minerals are unsaturated.

For division I. the scheme of subdivision which was used for the saturated rocks will serve again (see page 185), but for division II. some modification of that scheme is required. Details will be given in Chapter XIV.

REFERENCES.

Adams, F. D. and Barlow, A. E.—Canada, Geol. Survey, Mem. 6, 1910.
Allan, J. A.—Canada, Geol. Survey, Mem. 55, 1914.
Barlow, A. E.—Canada, Geol. Survey, Mem. 57, 1915.
Becker, E.—Zeit. deutsch. Geol. Gesellschaft, vol. 59, 1907.
Bell, J. M.; Clarke, E. C.; Marshall, P.—New Zealand, Geol. Surv. Bull. 12, 1911.
Benson, W. N.—Proc. Linn. Soc. N.S. Wales, 1913, *490, 662.*
Berwerth, F.—Jahrbuch Siebenbürg. Karpathenvereins, 1905, *1.*
Bowen, N. L.—Amer. Jour. Sci., 1922, *1.*
Brögger, W. C.—Eruptivgesteine des Kristianiagebietes, vol. I., 1894; vol. II., 1895; vol. III., 1898; vol. IV. (Fen district), 1921.
Brouwer, H. A.—Journal of Geology, 1917, *741.*
Busz, K.—Geological Magazine, 1896, *492.*
Cross, W.—Amer. Jour. Sci., 1897, *115.*
Daly, R. A.—Bull. Geol. Soc. America, 1910, *87.*
do. —Jour. of Geology, 1918, *97.*
Derby, O. A.—Amer. Jour. Sci., 1891, *311.*
Dixey, F.—Quart. Jour. Geol. Soc., 1922, *299.*
Duparc, L. and Grosset, A.—Récherches sur le district minier de Nicolai Pawda, Geneva, 1916.
Du Toit, A. L.—(Insizwa) Cape of Good Hope, Geol. Comm., 1910, *111.*
do. —(Tabankulu) S. Africa, Geol. Survey, Ann. Rep., 1912, *153.*
do. —(Kimberley) Cape of Good Hope Geol. Comm., 1906, *89.*

Foye, W. G.—Amer. Jour. Sci., 1915, *413*.
Graeff, F. F.—Baden, Geol. Landesanstalt, vol. 2, 1891, *405*.
Hall, A. L.—S. Africa, Geol. Survey, Mem. 15, 1920.
Harker, A.—Scotland, Geol. Survey, 1908 (Small Isles of Inverness).
Högbom, A. G.—Sweden, Geologiska Ondersökning, no. 148, 1895.
Holland, T. H.—India, Mem. Geol. Survey, vol. 30, pt. 3, 1901.
Humphrey, W. A.—S. Africa, Geol. Survey, Ann. Rep., 1911, 77.
Hussak, E.—Neues Jahrbuch Min., 1890, *166;* 1892, *146;* 1900, *22*.
Kaiser, E.—(Granitberg) Die Diamantenwüste Südwestafrikas, Berlin, 1926.
do. —(Monchique) Neues Jahrb. Min., B.B.39, 1914, *225*.
Kemp, J. F.—Amer. Jour. Sci., 1893, *298;* 1894, *339*.
Knight, C. W.—Amer. Jour. Sci., 1906, *286*.
Lacroix, A.—France, Service de la Carte géol., Bull. 42, 1894.
Lewis, J. V.—New Jersey, Ann. Rep. State Geologist, 1907.
Lightfoot, B.—S. Rhodesia, Geol. Survey, Short Report 19, 1926.
MacKenzie, J. D.—Canada, Geol. Survey, Museum Bulletin 4, 1914.
Morozewicz, J.—Tschermak's Min. Pet. Mitth., 1898.
Palmunen, M. K.—Fennia, vol. 45, 1925.
Pirsson, L. V.—(Corundum) Amer. Jour. Sci., 1897, *421*.
do. —(Missourite) Amer. Jour. Sci., 1896, *315*.
Quensel, P. D.—Bull. Geol. Inst. Upsala, vol. 12, 1914, *129*.
Ramsay, W.—Fennia, vol. 11, 1894; vol. 15, 1899.
Rogers, A. W.—Cape of Good Hope, Geol. Comm., 1911, 61.
Rogers, A. W. and du Toit, A. L.—Trans. S. Afr. Phil. Soc., 1904, *61*.
Ross, C. S.—Amer. Jour. Sci., 1926, *219*.
Scheumann, K.—Saxony, Konigl. Gesellsch. der Wiss., 1913, *607*.
do. —Centralblatt Min., 1922, *495*.
Shand, S. J.—(Scotland) Trans. Edinburgh Geol. Soc., 1910, *376*.
do. —(Sekukuniland) Trans. Geol. Soc. S. Africa, 1921, *111*.
do. —(Alkaline rocks) Proc. Geol. Soc. S. Africa, 1922, *19*.
Smyth, C. H.—Amer. Jour. Sci., 1913, *33*.
Spring, R.—Zeitschrift prakt. Geol., 1905.
Stansfield, J.—Geological Magazine, 1923, *433*.
Teall, J. J. H. and Horne, J.—Trans. Roy. Soc. Edinburgh, 1892, *163*.
do. —Geol. Magazine, 1900, *386*.
Thomas, H. H.—Quart. Jour. Geol. Soc., 1922, *229*.
Ussing, N. V.—Meddelelser om Grönland; Copenhagen, 1912.
Wagner, P. A.—The Diamond Fields of Southern Africa; Johannesburg, 1914.
do. —(Norite) S. Africa, Geol. Survey, Mem. 21, 1924.
Washington, H. S.—Journal of Geology, 1914, *742*.
Weed, W. H. and Pirsson, L. V.—(See Pirsson, L. V.).
Williams, J. F.—Arkansas, Geol. Survey, Ann. Rep., 1890.
Workman, R.—Geol. Magazine, 1911, *193*.

CHAPTER XIII.

THE UNDERSATURATED ROCKS.

PART II. A.—THE NON-ALKALINE DIVISION (EXAMPLES).

In this division we have to deal with rocks in which the alkalies are saturated with silica, but either lime, magnesia or alumina is undersaturated.

We may proceed, just as in the saturated class, to separate rocks in which orthoclase exceeds anorthite from those in which the reverse is the case. Since the rocks that we are now discussing have not, in the past, been separated from the corresponding saturated types, there are no distinctive names ready for them. Rather than invent new names, we shall provisionally attach the prefix *sub* to the names of the saturated types; thus the well-crystallised rocks in which orthoclase exceeds anorthite are *subsyenite*, the others *subdiorite*, the corresponding mesotype and melanocratic facies being *subshonkinite* and *subgabbro* respectively.

Among the subsyenites, we next distinguish a potassic group (Or>Ab) and a sodic group (Ab>Or), which we must call potash subsyenite and soda subsyenite respectively; and among the subdiorites a sodic group (Ab>An) and a calcic group (An>Ab) by name soda subdiorite and lime subdiorite. There will similarly be potash- and soda-subshonkinites and soda- and lime-subgabbros.

The soda subsyenites may be split up again, just as in the case of the soda syenites, into (*a*) albite subsyenite, with Or>3An, and (*b*) sub-akerite, with Or<3An. The corresponding mesotype rocks will be (*a*) albite subshonkinite, and (*b*) submonzonite.

In the case of rocks from which felspar is almost or quite absent, the name *peridotite* is available for all those which contain olivine, but (unless we use cromaltite and uncompahgrite) the melanite and melilite rocks will have to be nameless. As a general name for the group we may use *sub-perknite*.

The names for the dyscrystalline rocks will be formed by adding the prefix *sub* to trachyte, trachyandesite, andesite and basalt respectively.

The proposed subdivisions may be shown in tabular form as before. (Compare the table on page 185.)

I. Eucrystalline Rocks.

Leucocratic.	*Mesotype and Melanocratic.*
Potash subsyenite	Potash subshonkinite
Soda-subsyenite { *a*—albite subsyenite; *b*—sub-akerite	Soda subshonkinite { *a*—albite subshonkinite; *b*—submonzonite
Soda subdiorite	Soda subgabbro
Lime subdiorite	Lime subgabbro

II. Dyscrystalline Rocks.

Potash subtrachyte		(No name)
Soda subtrachyte	A—albite subtrachyte	(No name)
	B—sub-trachyandesite	(Sub-trachybasalt)
Soda sub-andesite		Soda sub-basalt
Lime sub-andesite		Lime sub-basalt

[It should be understood that these awkward designations are simply *provisional group-names,* and that there is no necessity to apply them to individual rocks.]

The peraluminous type now has corundum as its characteristic mineral; the metaluminous type is characterised either by melilite or by the association of olivine with hornblende or mica; and the subaluminous type contains olivine with or without pyroxene. A few peralkaline rocks contain melanite.

A. Subsyenites and Subtrachytes.

Syenites and trachytes with unsaturated magnesia, lime or alumina are quite uncommon. Corundum syenites are well developed in a few localities, but are absolutely unknown elsewhere. Olivine syenites and olivine trachytes have been described here and there, but it is seldom clearly established whether the olivine is fayalite or a magnesian variety. Melanite syenite, containing no nepheline, is a very rare rock, and only a few examples can be produced. Most sub-syenites belong to the soda group, and not a few of them to monzonite or trachyandesite; but as the number of available analyses is small, we

shall discuss them all under the general heading of sub-syenite and sub-trachyte.

Peraluminous Type.

The corundum syenites and pegmatites of Ontario have as their only felspar a microperthite in which albite is in excess of orthoclase. The only dark minerals, besides corundum, are large plates of biotite or muscovite, and sometimes hornblende. Corundum is variable in amount, but locally it makes up as much as 75 per cent. of the rock, and individual corundum crystals sometimes weigh more than thirty pounds (A. E. Barlow). The corundum pegmatites are intersected by quartz-felspar pegmatites which hold no corundum.

The corundum rocks of the Ilmen Mountains, Russia, are very similar to those of Ontario. The syenite of Nikolskaia Ssopka contains a microperthite in which albite slightly exceeds orthoclase. The corundum is in short, blue prisms; in one example analysed by Morozewicz, corundum made up 18.5 per cent. of the rock, and the only other heavy minerals present are a little biotite and some secondary white mica. At Sseljankina the rock holds a good deal of biotite; and in the corundum pegmatites of the Borsowka River there are traces of rutile, apatite and zircon.

In the corundum syenite of Coimbatore, Madras, the same mineralogical characters are repeated. T. H. Holland reports biotite, muscovite, apatite, zircon, spinel, chrysoberyl and pyrope as accessory constituents of a rock otherwise composed of microperthite and corundum.

Metaluminous and Subaluminous Types.

The only examples of these types occur in minor intrusions and surface flows. The intrusions are generally metaluminous, the lavas mostly subaluminous, so far as data are available.

J. J. O'Neill has described a rock occurring on St. Hilaire Mountain, Quebec, which holds over 70 per cent. of soda-orthoclase, together with olivine, brown hornblende, biotite, apatite and iron ore, in that order of abundance.

A mestoype olivine-syenite or shonkinite was described by R. A. Daly from Christina Lake and other points in British Columbia. It is a coarse grained, dark gray rock composed of soda-orthoclase, labradorite, diopside, olivine, and large foils of dark green biotite. The mode is :—

soda-orthoclase	45.1	biotite	4.2
diopside	24.5	apatite	0.4
labradorite	10.6	magnetite	3.5
olivine	10.7	Colour index	(43)

W. C. Brögger describes an olivine-monzonite at Smalingen, Sweden, which has the following composition :—

orthoclase	20	biotite	6
andesine	33	magnetite	3
pyroxene	25	apatite, etc.	1
olivine	12	Colour index	(47)

A similar type of rock occurs at Kentallen and a few other places in Scotland, and has received the name of " kentallenite." According to J. J. H. Teall, the Kentallen rock is composed of olivine and augite, embedded in a groundmass of biotite, plagioclase and orthoclase, the last two approximately equal in quantity.

Some rocks that have been described as " minette " fall in here. L. V. Pirsson has described such rocks in Montana, and the following modes refer to minettes of Yogo Peak (1) and the Highwood Mountains (2).

	(1)	(2)
alkali-felspar	25	39.2
andesine	10	—
biotite	18	16.8
pyroxene	35	29.3
olivine	7	7.6
hornblende	5	—
magnetite		6.9
apatite		1.2
Colour index	(65)	(61)

The " ciminite " of Monte Cimini, Italy, as described by H. S. Washington, ranges from olivine trachyte to olivine trachy-andesite. The former variety is illustrated by mode 1, the second by mode 2 below :—

	(1)		(2)
soda-orthoclase ($Or_{10}Ab_3$)	50.7	orthoclase	39.4
plagioclase (Ab_1An_2)	13.1	albite	15.2
augite	23.2	anorthite	22.8
olivine	11.2	olivine	10.2
magnetite	0.9	diopside	8.7
apatite	0.9	magnetite	3.7
Colour index	(36)		(23)

Peralkaline Type.

A. C. Lawson gave the name " malignite " to a series of soda-rich rocks occurring at Poohbah Lake, Ontario. Among these rocks is a melanite-syenite, consisting of large, flesh-coloured crystals of microperthite which are embedded in a greenish holocrystalline matrix of felspar, soda-diopside, melanite, biotite, sphene and apatite. The proportions of these minerals are not stated, but the rock appears to be mesotype.

P. Eskola has described syenitic rocks with a considerable content of deep brown garnet (andradite or melanite) at Sviatoy Noss in Transbaikalia. The composition of two of these rocks is given below. In each case there is a slight excess of silica, but Eskola states that " no quartz was detected under the microscope in spite of much search with convergent light, and it may be that the result is due to an accumulation of analytical errors."

orthoclase	24.8	31.1
albite	41.5	37.7
anorthite	3.2	10.8
soda-diopside	17.1	5.7
andradite	9.0	10.2
sphene	1.8	1.4
apatite	1.1	0.3
magnetite	0.5	0.7
extra silica	1.1	1.9
Colour index	(30)	(20)

Melanite syenite has been recorded at several points in the limestone districts of Assynt, Scotland. At Loch Borolan it forms a transition rock between quartz-bearing syenites and nepheline-syenite, and the melanite is associated with biotite (S. J. S.); near Loch Ailsh, J. Phemister has found another variety consisting of soda-rich microperthite, ægirine and melanite.

No quantitative description of a melanite trachyte has been traced.

B. Sub-diorites and Sub-andesites.

It was shown in Chapter IX. that diorites and andesites, as we have defined these rocks, are quite uncommon, and that the frequent occurrence of these names in petrographic literature is a consequence of the prevailing disregard of quantitative data.

Subdiorites and subandesites, within the meaning of our definition, are fully as scarce as the saturated types, and only a very few examples are available for discussion here.

Peraluminous Type.

The " plumasite " of Plumas Co., California, as described by A. C. Lawson, is a corundum-oligoclase rock, the proportions of these minerals being, in a typical instance, oligoclase 83, corundum 16. Chemical analysis of the rock shows that no orthoclase is present at all.

A rock described by Adams and Barlow under the name of " dungannonite " is virtually the same as Lawson's plumasite. It consists of plagioclase ranging from albite to andesine, which makes up 75 to 95 per cent of the rock, together with corundum, biotite, muscovite, calcite, magnetite and scapolite. Nepheline is sometimes present in addition, taking the rock over to the alkaline division of the undersaturated rocks.

The corundum pegmatites of the Transvaal are also similar to the plumasite of California. As described by A. L. Hall, they consist of plagioclase which varies from oligoclase to andesine (and is apparently free from potash, according to the analyses available), together with grey corundum and some biotite. Margarite and gibbsite are secondary products. The proportion of corundum is variable, but in an average specimen of reef Hall found it to be 40 per cent. by weight, which is equal to 30 per cent. by volume.

Metaluminous and Subaluminous Types.

The " essexite " of Brome Mountain, Quebec, was described by J. A. Dresser; it consists, to the extent of about 90 per cent., of labradorite or bytownite, with a little microperthite. The dark constituents are hornblende, augite, biotite, olivine, sphene, apatite and magnetite. There is a little secondary matter in the interstices which may possibly represent nepheline, but no fresh nepheline is present. The rock is therefore a lime-(sub)diorite.

The norite of Sierra Leone has facies which are sufficiently felspathic to fall into lime-(sub)diorite. An estimation of the volumetric proportions of the minerals in this rock gave (S. J. S.)

labradorite	74	diallage, hypersthene...	9
olivine	14	magnetite	2.3
		Colour index	(25)

A. Harker has given the modes of some gabbros and dolerites of the island of Skye, and it appears that these, too, fall within the sub-diorite group of our system. A gabbro of the Cuillin Hills gave 80 per cent. (by weight) of labradorite; 16 of augite and olivine; 2 of ortho-pyroxene, and 2 of magnetite. A dolerite near Portree was found to hold roughly 77 per cent. of labradorite, 11 of augite, and 12 of olivine and accessory minerals.

The " mugearite " type of basalt, which was first described by Harker in the same district, falls partly into soda-(sub) andesite. One example which Harker investigated, contained about 70 per cent. (by weight) of felspar, which is partly oligoclase and partly orthoclase. Olivine is more abundant than augite, and the rock is also unusually rich in apatite. The mode is

oligoclase	57·5	olivine, ore, augite...	26.5
orthoclase	12.5	apatite	3·5
		Colour index (30 by weight)	

The composition of the felspar, as a whole, is Or 8, Ab 34, An 20.

Some of the lavas of Pembrokeshire, to which H. H. Thomas gave the name " marloesite," appear to fall in soda-(sub)andesite. The felspar is albite-oligoclase, and the proportion of dark minerals may be as low as 15 per cent.

C. Sub-Gabbros and Sub-Basalts.

Peraluminous Type.

This type is represented by the " kyschtymite " or corundum-anorthosite of the Ilmen Mountains in Russia. J. Morozewicz gives the following data for an example of this rock :—

anorthite	38
biotite	10
corundum	47·5
spinel	3 to 4
Colour index	(62)

The order of crystallisation was zircon, spinel, corundum, anorthite, biotite.

Metaluminous Type.

The " essexites " or " olivine-gabbro-diabases " of Norway are examples of metaluminous sub-gabbro. The three analyses given below are furnished by W. C. Brögger; two of them represent mesotype rocks, and the third is melanocratic.

	Dignaes	*Sölvsberget*	*Brandberget*
plagioclase	64	46	12
pyroxene	10	26	69
biotite	8.5	9.5	3
olivine	9	12.5	5
ore	6.5	5	7
apatite, etc.	2	1	4
Colour index	(36)	(54)	(88)

Biotite is sometimes found in olivine-gabbro and olivine-norite in more than merely " accessory " proportions. W. H. Emmons describes an olivine-gabbro at Haystack, Montana, which has the following composition :—

orthoclase	4.9	olivine	6.8
albite	19.2	biotite	4.5
anorthite	26.7	ore	5.8
pyroxene	30.9	apatite	1.2
		Colour index	(49)

C. Doelter has described a very similar rock at Ricoletto, Tyrol. This is a dark rock with large black augite crystals and a few large biotite tables, as well as " reaction rims " of biotite about the augite and magnetite grains. The plagioclase is highly calcic, and a little orthoclase was the last mineral to crystallise. The mode is

orthoclase	5 to 7	biotite, olivine	5 to 10
anorthite	35 ,, 40		
augite	40	magnetite	7 ,, 10

An olivine gabbro described by L. V. Pirsson at Tripyramid Mountain, New Hampshire, is also biotite-bearing, as the following mode shows :—

labradorite	63	olivine	10
biotite	5	ore	6.7
augite	14	apatite	1.3
		Colour index	(37)

Lavas of this type seem to be scarce. V. M. Goldschmidt has described lavas of N.W. Spitzbergen which hold soda-plagioclase (Ab_3An) together with titanaugite, olivine, enstatite, brown hornblende of late crystallisation, ore and glass. These lavas are remarkable on account of the abundant nodules of enstatite, olivine, diopside and spinel which they carry.

Rocks which carry melilite together with plagioclase, but without nepheline, would also fall in this class. Only one such rock is known, which was discovered by Ramsay and Nyholm at

Kuolajärvi, Finland. The rock has insets of melilite, augite and ægirine, and biotite in a groundmass which contains labradorite. Olivine is absent.

Subaluminous Type.

The felspar in these rocks is generally a calcic variety, hence soda-(sub)gabbro is unusual. One rock in which albite exceeds anorthite is the dolerite or "essexite" (both names have been used)* of the Prospect intrusion, near Sydney, New South Wales. This rock holds plagioclase of variable composition, but the mean is Ab_4An_3. The mode is given as follows, by Jevons and colleagues :—

plagioclase	36	ilmenite and magnetite	13
titanaugite	36	accessory and secondary	5
olivine	10	Colour index	(64)

In the majority of cases the felspar is labradorite to bytownite. The olivine gabbro of Pigeon Point, Minnesota, has the following composition, according to W. S. Bayley :—

labradorite (Ab_3An_4)	60	augite	27
olivine	10	apatite, etc.	3
		Colour index	(40)

The olivine-gabbro of Volpersdorf, Silesia, has been examined by P. Tschirwinsky, who gives the following mode :—

plagioclase	57.2	olivine	14.3
ortho-pyroxene	2.4	titanomagnetite	0.1
clino-pyroxene	25.9	pyrites	0.1
		Colour index	(40)

A higher colour index is exhibited by an olivine-diabase (dolerite) in Davidson Co., North Carolina, which was described by J. E. Pogue. The mode is

bytownite (Ab_1An_3)	45.6	olivine	17.4
augite	35.3	magnetite	1.8
		Colour index	(54)

The gabbro of Tutuila, Samoa, has the following composition (R. A. Daly) :—

bytownite (Ab_3An_7)	44.6	ilmenite and magnetite	6.0
augite	24.0	apatite	0.7
olivine	24.7	Colour index	(55)

*The name of this rock was changed from dolerite to essexite on the sole ground that it is associated with alkaline rocks. What will become of systematic petrography if every rock changes its name according to the company it keeps?

The name " eucrite " is sometimes given to gabbros in which the felspar approaches pure anorthite. Such rocks have been studied by A. Harker in the western islands of Scotland, and the following data relate to a eucrite from the island of Rum :—

bytownite ...	48 (by weight)	olivine ...	9
hypersthene } augite ... }	40	ores	3
		Colour index	(52)

The " allivalite " of A. Harker is an anorthite-olivine rock of which anorthite constitutes half or more. " Harrisite " is the complementary type in which olivine preponderates. Such rocks are well developed in the islands of Rum and Mull; they differ from eucrite only by the virtual absence of pyroxene. Picotite or chromite is a common accessory constituent.

Melanocratic varieties of sub-gabbro often receive the name of *picrite*. Harker describes a picrite from the island of Skye, of which olivine forms 50 to 75 per cent., the remainder being augite and anorthite.

An olivine-gabbro described by R. A. Daly, in Hawaii, might also be called picrite. The mode is

labradorite	27	ore	1.7
augite	31	apatite	0.3
olivine	40	Colour index	(73)

An extremely melanocratic type, which is almost a peridotite, is the " cumberlandite " of Rhode Island, described by Warren and Powers. This rock contains 30 per cent. of iron, and was once mined for use as an iron ore. The mode is

labradorite	10	magnetite	18
olivine (rich in iron)	40	ilmenite	20
serpentine, etc.	9	spinel	3
		Colour index	(90)

Coming now to the dyscrystalline facies, we find that J. V. Harrison has described a good example of a soda-(sub)basalt in the Kilsyth Hills, Scotland. The rock has insets of andesine in a groundmass of oligoclase and dark minerals. Chemical analysis shows that Or, Ab and An are present in the proportion of 9 : 40 : 12. The mode of this rock is

felspar	65.5	ores	1.1
augite	23.0	apatite	0.4
olivine	1.0	Colour index	(34)

Basalts in which the albite and anorthite molecules are about equally abundant were described by H. S. Washington on the islands of Linosa and Pantelleria, as follows :—

	Linosa	*Linosa*	*Pantelleria*
plagioclase (Ab_1An_1)	57	47	51
augite	26	11	22
olivine	6	28	9
titanomagnetite	10	10	14
apatite	1	1	2
glass	—	3	—
Colour index	(43)	(53)	(47)

Olivine basalts in the San Francisco volcanic district of Arizona were described by H. H. Robinson. The following data relate to basalts of Cedar Ranch Mesa (1) and Kendrick Peak (2) :—

	(1)	(2)
orthoclase	1.4	—
labradorite (Ab_3An_4)	52.6	57.8
augite	22.0	28.5
olivine	11.7	8.4
magnetite	4.3	5.4
calcite, etc.	8.0	—
Colour index	(46)	(42)

These figures are close to those given by Harker, for an olivine basalt of the island of Skye :—

labradorite	54	titanomagnetite	8
augite	29	apatite	0.2
olivine	9	Colour index	(46)

Basalts are not as a rule so rich in anorthite as eucrites, but J. S. Flett has described ejected blocks among the volcanic ash of St. Vincent, West Indies, which consist of anorthite, olivine, augite, hypersthene, and a little hornblende, in grains measuring from half an inch downwards. The grains are joined together by thin films of brown glass, full of magnetite dust, and the crystals contain glass enclosures.

R. A. Daly describes a melanocratic basalt in Hawaii, which has large insets of olivine in a fine-grained base of augite and labradorite. The mode of this rock is

labradorite...	35.7 (weight)	ore	5.0
olivine	32.0	apatite	0.3
augite	27.0	Colour index	(64)

Such olivine-rich basalts may be described as picrite-basalt.

D. Sub-Perknites.

(Peridotites, Cromaltites, Uncompahgrites, and Melilite Basalts.)

The most general name for a rock composed almost wholly of dark minerals, including olivine, is *peridotite;* when the olivine is unaccompanied by other silicates (except in trivial quantity) the name *dunite* is used. There is no general name for melilite rocks. Those which carry only melilite and pyroxene have been called melilitite; this, with the addition of olivine, becomes melilite-basalt, and a melilite-basalt with much biotite is called "alnöite." Pyroxenites which carry an unsaturated garnet (usually melanite) are very uncommon rocks; the name "cromaltite" has been given to a rock of this type in the north of Scotland, which is a product of reaction between alkaline magma and limestone.

Metaluminous Type.

H. S. Washington has described a hornblende-rich peridotite at Bahia, Brazil, with the following simple composition :—

hornblende	91.3
olivine	3.6
magnetite	5.1

In the hornblende-peridotite of Plumas Co., California, described by H. W. Turner, hornblende is quite subordinate to olivine. This rock holds

olivine	45	hornblende	19.6
serpentine	33	magnetite	1.4

A mica-rich peridotite, which is comparable with the micaceous type of kimberlite, is described in Arkansas by Miser and Ross. The mode is

phlogopite	56	augite	6
olivine, serpentine	35	perovskite	1
		magnetite	2

Mica is also a large constituent of the "scyelite" which was described by J. W. Judd in Caithness, Scotland. It contains

hornblende	58.5	serpentinised olivine	22
mica	18.5	magnetite, etc.	1

In the next four examples, pyroxene is an important constituent in addition to hornblende or mica. The first is a peridotite of Monzoni, Tyrol, described by W. C. Brögger :—

plagioclase	10	olivine (serpentine)	10
biotite	10	magnetite	5
hornblende	10	rest	5
augite	50		

W. Tyrrell describes a metaluminous peridotite near Ayr, Scotland, which has the following mode :—

olivine	65.2	biotite	2.0
titanaugite	20.5	ore	2.3
hornblende	10.0		

A hypersthene-bearing example is described by H. S. Washington at Bahia, Brazil; it forms the outer facies of an intrusive body, the core of which is the hornblende peridotite described above. The mode is

hornblende	29.6	olivine	7.5
hypersthene	59.4	spinel	3.5

The " yamaskite " of Rougemont, Quebec, is a pyroxene-rich peridotite with a small content of anorthite. J. J. O'Neill gives the following statement of the composition of yamaskite :—

anorthite	6.1	hornblende	8.8
augite	70.7	biotite	0.5
olivine	13.4	ore	0.5

The kimberlite or " blue ground " of the South African diamond fields is a more or less highly serpentinised peridotite. P. A. Wagner distinguishes two varieties, one of which is rich in mica, holding roughly 50 per cent. of phlogopite, while the other is more basaltic in appearance and holds only 3 or 4 per cent. of mica. Wagner describes the very fresh kimberlite of De Beers Mine (2,040 ft. level), as a dark, basaltic rock, holding rounded olivine crystals and scales of brown mica, as well as occasional grains of ilmenite, enstatite, pyrope and diopside, in a compact groundmass which contains some of the above minerals, with perovskite, ores and calcite in addition.

Rocks which contain melilite, with or without olivine (and of course without felspar or felspathoid) have their place here. The most remarkable of these rocks is the " uncompahgrite " of

E. S. Larsen and J. F. Hunter, from Gunnison Co., Colorado. This is a coarse-grained rock, about two-thirds of which is melilite. Crystals and grains of pyroxene, magnetite, perovskite, apatite, biotite, and calcite are enclosed in large crystals of melilite which are sometimes as much as a foot in diameter. The second mineral, as regards abundance, is generally perovskite. The melilite crystals alter into a fine-grained aggregate of garnet, diopside and vesuvianite. This is one of the very few eucrystalline rocks which contain melilite.

The alnöite of Alnö, Sweden, is a micaceous type of melilite-basalt which has large insets of biotite, together with titanomagnetite, pyroxene, olivine and apatite, in a groundmass of mica, melilite and calcite. Perovskite, chromite, pyrrhotite and melanite are also present in some cases (A. G. Högbom).

The alnöite of Ile Cadieux, Quebec, contains the same minerals as the Swedish alnöite, with the addition of scapolite and monticellite. Biotite is the most abundant mineral, and monticellite next. N. L. Bowen gives the following mode :—

biotite	30 (by weight)	melilite	3
monticellite	25	apatite	4
olivine	15	perovskite	
augite	10	and ore	7
		carbonates..	6

The " farrisite " of W. C. Brögger, from the Christiania district of Norway, is a fine-grained dyke rock containing much brown hornblende, but little mica, in addition to melilite and pyroxene. The mode is

melilite	35.0	diopside	24.5
biotite	5.0	olivine	1.0
hornblende	32.5	ore, apatite	2.0

A. W. Rogers and A. L. du Toit have described melilite-basalts at various localities in South Africa. At Sutherland, the rock has insets of olivine and biotite in a groundmass of melilite, magnetite, perovskite and calcite. The widely known melilite basalt of Spiegel River, in the district of Riversdale, has insets of olivine in a base of melilite, augite, perovskite, magnetite and glass.

The " rodingite " of Dun Mountain, New Zealand, is a coarse-grained rock consisting of about 66 per cent. of grossularite and 33 per cent. of diallage (Bell, Clarke and Marshall). The grossularite holds some 17 per cent. of iron oxides, so it is half-way to melanite. Similar rocks have been found in New

South Wales, but W. N. Benson considers both occurrences to have resulted from the metamorphism of eucrites under pressure.

Subaluminous Type.

These rocks consist largely of olivine and various pyroxenes, mica and hornblende being either absent or present only in trivial amount. The typical " dunite " of Dun Mountain, New Zealand, is almost a pure olivine rock, grains of chrome spinel and rare crystals of diopside being the only other constituents (Bell, Clarke and Marshall). It is associated with various pyroxene-bearing peridotites and with pyroxenites.

A remarkable porphyritic dunite has been described by A. Harker, in the island of Skye. It has large crystals of olivine set in a groundmass of smaller olivine grains and octahedrons of picotite (chrome-spinel).

Olivine rocks are often rich in oxidic or sulphidic ores. M. K. Palmunen describes an " ilmenite-magnetite olivinite " at Susimäki, Finland, which carries a third of its weight of iron oxides. The olivine is itself richer than usual in iron, being about $Fo_{55}Fa_{45}$, and a little brown hornblende is present. The mode is

olivine ...	60.3 (by weight)	ilmenite ... } magnetite }	36.3
hornblende	3.0		
spinel ...	0.2	sulphides ...	0.2

A pyrrhotite-peridotite has been described by E. S. Bastin in Knox Co., Maine. It holds 60 per cent. of olivine, 22.5 per cent. of pyrrhotite, 10 per cent. of magnetite, and small quantities of labradorite, hornblende, biotite, spinel and copper pyrites.

An unusual variety of peridotite or dunite is found in the Transvaal, in addition to the ordinary magnesian kind. This rock is dark brown in colour, and remarkably dense, owing to the high iron-content of the olivine, which has approximately the composition Fo_1Fa_1. P. A. Wagner gives the following mode :—

olivine (Fo_1Fa_1)	93.2	hornblende	1.5
diopside	5.0	ore	0.3

Perhaps the commonest type of peridotite is that which contains ortho-pyroxene along with olivine; the name " harzburgite " is given to such rocks. Harzburgite forms a facies of nearly every important body of olivine rocks, such as Dun Mountain, New Zealand; the Great Dyke of Rhodesia; the Serpentine Belt of New South Wales; and the peridotites of the Ural Mountains.

Peralkaline Type.

Two examples of melanite-pyroxenite may be quoted here. The first occurs in Assynt, Scotland, and was described under the name of " cromaltite " (S. J. S.); the second is a marginal facies of the Ice River alkaline complex in British Columbia (J. A. Allan). The modes are

	(1)	(2)
soda-diopside	51.9	65
melanite	15.6	5
biotite	16.5	—
sphene	—	15
ore	5.2	5
apatite	4.2	10
rest	6.6	

REFERENCES.

Adams, F. D. and Barlow, A. E.—Canada, Geol. Survey, Mem. 6, 1910.
Allan, J. A.—Canada, Geol. Survey, Mem. 55, 1914.
Barlow, A. E.—Canada, Geol. Survey, Mem. 57, 1915.
Bastin, E. S.—Jour. Geol. 1908, *131*.
Bayley, W. S.—U.S. Geol. Survey, Bull. 109, 1893, *34*.
Bell, J. M.; Clarke, E. C.; Marshall, P.—New Zealand, Geol. Survey, Bull. 12, 1911.
Benson, W. N.—Proc. Linn. Soc. New S. Wales, 1913, *662*.
Bowen, N. L.—Amer. Jour. Sci., 1922, *1*.
Brögger, W. C.—Eruptivgesteine des Kristianiagebietes, 1894-1898.
do. —Quart. Jour. Geol. Soc., 1894, *15*.
Daly, R. A.—Canada, Geol. Survey, Mem. 38, 1912, *310, 336, 356*.
do. —(Hawaii) Jour. Geol., 1911, *289*.
do. —(Samoa) Carnegie Inst. Washington, Publ. 340, 1924, *95*.
Doelter, C.—Tschermak's Min. Pet. Mitth., 1902, *73*.
Dresser, J. A.—Canada, Geol. Survey, Ann. Rep., 1906.
Emmons, W. H.—Jour. Geol. 1908, *212*.
Eskola, P.—Finska Vetenskaps Soc., Förhandlingar, 1921.
do. —Videnskaps Selskabets Skrifter, 1921, no. 8.
do. —(Orijärvi) Finland, Bull. Comm. géol., no. 40, 1914.
Flett, J. S.—Phil. Trans. Roy. Soc., 1908.
Goldschmidt, V. M.—Videnskaps Selskabets Skrifter, 1911.
Hall, A. L.—S. Africa Geol. Survey, Mem. 15, 1920.
Harker, A.—Scotland, Mem. Geol. Survey (Skye), 1904.
do. — do. do. (Small Isles), 1908.
Harrison, J. V.—Trans. Geol. Soc. Glasgow, 1915, *315*.
Högbom, A. G.—Sveriges Geologiska Undersökning, no. 148, 1895.
Holland, T. H.—India, Mem. Geol. Survey, vol. 30, pt. 3, 1901.
Jevons, H. S.—Proc. Roy. Soc. New S. Wales, 1911 *445*.
Judd, J. W.—Quart. Jour. Geol. Soc., 1885, *401*

Larsen, E. S. and Hunter, J. F.—Jour. Washington Acad. Sci., 1914, *473*.
Lawson, A. C.—California, Bull. Dept. Geol. 1896, vol. 1, *33*.
do. —(plumasite) do. do. do. vol. 3, *219*.
Miser, H. D. and Ross, C. S.—U.S. Geol. Survey, Bull. 735, *279*.
Morozewicz, J.—Tschermak's Min. Pet. Mitth., 1902, *238*.
O'Neill, J. J.—Canada, Geol. Survey, Mem. 43, 1914, *72, 77*.
Palmunen, M. K.—Fennia, 45, 1925, *4*.
Phemister, J.—Scotland, Geol. Survey (Strath Oykell), 1926, *22*.
Pirsson, L. V.—(Yogo Peak) U.S. Geol. Survey, 20 Ann. Rep., pt. 3, 1899, *257*.
do. —(Highwood Mts.) U.S. Geol. Survey, Bull. 237, 1905.
do. —(Tripyramid Mtn.) Amer. Jour. Sci., 1911, *269*.
Pogue, J. E.—Proc. U.S. National Museum, 1910, *475*.
Quensel, P. D.—Bull. Geol. Inst. Upsala, vol. II., 1912, *253*.
Ramsay, W. and Nyholm, E. T.—Comm. Geol. Finlande, Bull. 1, 1895.
Rogers, A. W. and du Toit, A. L.—Trans. S. Afr. Phil. Soc., 1904, *61*.
Robinson, H. H.—U.S. Geol. Survey, Prof. Paper 76, 1913, *149*.
Shand, S. J.—(Scotland) Trans. Edinburgh Geol. Soc., 1910, *376*.
do. —(Sierra Leone) Geol. Mag., 1918, *21*.
Teall, J. J. H.—Scotland, Geol. Survey Ann. Rep., 1906, *22*.
Thomas, H. H.—Quart. Jour. Geol. Soc., 1911, *175*.
Tschirwinsky, P.—Centralblatt Min., 1925, *275*.
Turner, H. W.—U.S. Geol. Survey, 20 Ann. Rep., 1892, *476*.
Tyrrell, G. W.—Trans. Geol. Soc. Glasgow, 1918, *339*.
do. —Quart. Jour. Geol. Soc., 1917, *84*.
Wagner, P. A.—The Diamond Fields of S. Africa, Johannesburg, 1914.
do. and Mellor, E. T.—Trans. Geol. Soc. S. Afr., 1925, *1*.
Warren, C. H. and Powers, S.—Bull. Geol. Soc. America, 1914, *435*.
Washington, H. S.—(Brazil) Amer. Jour. Sci., 1914, *79*.
do. —(Hawaii) Amer. Jour. Sci., 1923, *478*.
do. —(Linosa) Jour. Geol. 1908, *1*.
do. —(Pantelleria) Jour. Geol. 1914, *653*.
do. —(Sardinia) Amer. Jour. Sci., 1913, *577*.
do. — do. Jour. Geol., 1897, *30*.
do. —(Rome) Carnegie Inst. Washington, Publ. 57, 1906.

CHAPTER XIV.

THE UNDERSATURATED ROCKS.

PART II. B.—THE ALKALINE DIVISION (EXAMPLES).

With a large number of leucocratic minerals present, the rational subdivision of this group becomes a difficult matter. Even if all the soda-felspathoids (nepheline, sodalite, haüyne, nosean, cancrinite and analcime) are grouped together in opposition to the potash-felspathoid (leucite), that leaves us still with two kinds of felspathoid in addition to the usual three kinds of felspar. As regards the felspathoids, a sharp line of division can be drawn between rocks which contain leucite and those which do not, and since the inversion point of orthoclase-leucite falls within the range of magmatic temperatures, it is important that such a line should be drawn; but no such precise separation can be effected with reference to the kind of felspar present. If we continue our former practice of comparing the ratio of orthoclase to anorthite molecules in the felspar, the results will not be comparable with those reached in the earlier classes, for in many lavas a large part of the potash is present in leucite instead of orthoclase. It thus becomes necessary to replace the orthoclase-anorthite ratio by the ratio of *orthoclase + leucite* to anorthite. This gives us the following primary classification :—

Group I.—Or + Lc > An	(a) Leucite present
	(b) Leucite absent
Group II.—Or + Lc < An	(a) Leucite present
	(b) Leucite absent

The case of rocks which contain felspathoids without any felspar presents no difficulty; such rocks belong to the first group, and differ from the other members of the group only by being more highly undersaturated. For the first group the general name of *syenoid* will be used, with *phonolite* for the corresponding lavas; for the second group, either *dioroid* or *gabbroid*,

according to the colour index of the rock. No names are directly available for the lavas of the second group; however reprehensible such a proceeding may be, it seems better to seize upon *tephrite* and *basanite*, and redefine them according to our needs, than to invent entirely new names. Further steps in classification will be indicated during the discussion of the primary groups.

GROUP I. (a).

Leucite-Syenoids and Leucite Phonolites.

The only known example of a leucite-syenoid—that is, a eucrystalline rock containing fresh leucite—is the rock called "missourite" by W. H. Weed and L. V. Pirsson. It forms a stock, measuring about two and a half miles by half a mile, in the Highwood Mountains of Montana. All other representatives of this group are lavas, for which we shall use leucite phonolite as a general name. It is most desirable that this double-barrelled name should be replaced by a single word; for this purpose no name could be more suitable than *italite*, since every possible variety of leucitic lava has been found in Italy. Unfortunately this name has been bestowed by H. S. Washington upon one of the rarest of these varieties.

Among the leucite-phonolites, as defined above, there are two kinds which are currently distinguished by entirely different names. In one, the felspar is mainly or entirely soda-orthoclase; this is what is generally understood by leucite-phonolite (also called leucite-trachyte). In the other there is a good deal of calcic plagioclase, ranging from labradorite to nearly pure anorthite; such rocks are known as "leucite-tephrite." This distinction may be made quantitative by the use of the orthoclase-anorthite ratio. Those leucite-phonolites in which the felspar has Or>An we shall call *trachytic leucite-phonolite;* those in which An>Or, *tephritic leucite-phonolite.* (Were it not for the circumstance mentioned in the previous paragraph, we might have called these potash-italite and lime-italite respectively.) For the kind of lava which holds little or no felspar of any kind, the name *leucitite* is customary.

No peraluminous rocks are known in this group.

Metaluminous Type.

"Missourite" has the following composition (Weed and Pirsson):—

leucite	16 (weight)	augite	50
analcime	4	olivine	15
zeolites	4	ore	5
biotite	6	Colour index	(76)

Apart from the above example, this type of rock is represented only by effusive forms. The first three illustrations relate to rocks from the volcanic region about Rome; they have been described by H. S. Washington under the name of leucite-trachyte. In our terminology, they are trachytic leucite phonolites.

	(1)	(2)	(3)
soda-orthoclase	39.6	47.7	30.0
labradorite	17.5	16.3	24.5
leucite	31.4	16.9	15.7
nepheline	—	—	0.9
biotite	2.3	3.7	2.3
augite	5.3	10.3	18.3
magnetite	3.2	3.8	3.4
apatite	0.7	0.5	—
Colour index	(11)	(18)	(27)

The next two rocks are also from the Roman region; they carry more plagioclase than orthoclase, for which reason Washington has called them leucite-tephrite. The second one is a tephritic leucite-phonolite.

soda-orthoclase (Or_2Ab_1)	26.0	(Or_3Ab_1)	10.5 (weight)
labradorite (Ab_2An_3)	28.0	(Ab_1An_1)	26.1
leucite	15.8		29.0
nepheline	1.0		2.8
biotite	3.4		—
hornblende	—		2.0
augite	16.8		21.6
olivine	2.0		5.0
magnetite	6.0		2.0
apatite	1.0		1.0
Colour index	(29)		(31)

In a curious rock which W. Cross has named "madupite," from the Leucite Hills of Wyoming, no leucite is developed at all, and the rock consists of diopside, phlogopite and a little perovskite in a glassy base which has the chemical composition of

leucite. If the magma had crystallised completely, this rock would have been composed of :—

leucite	20.3	diopside	46.1
nosean	6.5	accessories	8.2
phlogopite	18.9	Colour index	(73)

To the metaluminous type we must add the melilite-bearing leucitites, for which H. S. Washington has proposed to revive the old name *cecilite*. The following examples are all from the Roman region.

	(1)	(2)	(3)	(4)	
anorthite	—	3.6	3.8	5.3	(weight)
leucite	60	41.9	39.7	30.0	
nepheline	—	7.3	9.8	5.8	
augite	20	22.6	28.9	50.4	
olivine	—	6.8	1.6	2.3	
melilite	18	12.6	12.2	3.4	
magnetite	2	4.0	3.0	1.8	
apatite	—	1.2	1.0	1.0	
Colour index	(40)	(47)	(47)	(59)	

Subaluminous Type.

The first two of the following examples are trachytic leucite phonolites; the third is a mesotype leucitite without any felspar at all. All are from the Roman region.

	(1)	(2)	(3)
soda-orthoclase	60.7	55.2	—
labradorite	11.3	20.1	—
leucite	8.8	1.7	48.2
nepheline	3.5	4.0	6.0
augite	8.9	13.1	42.8
olivine	1.1	1.7	—
magnetite	4.7	3.4	3.0
apatite	1.0	0.8	—
Colour index	(16)	(19)	(46)

Some of the lavas of the Roman region are largely composed of glass. The apparent composition of two such rocks is given below, and it is followed in each case by the calculated composition, obtained by chemical analysis. It will be noticed that in spite of the predominance of labradorite in the crystalline portion, both rocks are trachytic, not tephritic, phonolites.

	(observed)	*(calculated)*	*(observed)*	*(calculated)*
soda-orthoclase	1.1	48.3	1.1	47.8
labradorite	2.9	18.3	14.1	19.9
leucite	16.6	16.8	38.1	17.2
nepheline	—	6.5	—	—
augite	4.9	6.2	1.4	8.2
ore	1.4	3.9	—	5.4
groundmass	73.1	—	45.3	—
Colour index		(10)		(14)

The following are examples of tephritic leucite-phonolite from the Roman region. Washington calls them all leucite-tephrite :—

	(1)	(2)	(3)	
soda-orthoclase	22.2	13.5	17.5	(weight)
labradorite	35.6	23.8	16.8	
leucite	25.5	44.2	37.1	
nepheline	—	1.7	4.6	
augite	9.1	7.9	18.6	
olivine	2.3	4.2	—	
magnetite	4.0	3.8	4.4	
apatite	1.3	0.9	1.0	
Colour index	(17)	(17)	(24)	

The remaining examples are all mesotype. The first four are Roman lavas, and Washington has named them all leucitite; the next three, from the same region, he names leucite-tephrite. It is very difficult, from a mineralogical standpoint, to see any justification for the difference in name.

	(1)	(2)	(3)	(4)	
soda-orthoclase	8.5	6.5	—	—	(weight)
labradorite-anorthite	13.9	15.0	14.1	10.5	
leucite	36.2	32.5	35.0	32.3	
nepheline	8.3	6.8	5.1	3.4	
augite	30.4	32.0	41.0	47.1	
olivine	—	2.3	4.0	4.0	
magnetite	4.7	2.6	0.5	1.1	
apatite	1.0	1.3	0.3	1.0	
Colour index	(36)	(38)	(46)	(53)	

	(5)	(6)	(7)
soda-orthoclase	—	5.4	—
labradorite	17.4	23.2	13.8
leucite	34.9	31.5	35.6
nepheline	9.0	—	9.9
augite	30.3	33.8	31.8
olivine	5.6	—	6.1
ore	1.5	5.5	1.0
apatite	1.3	0.6	1.8
Colour index	(39)	(40)	(41)

As an example of a melanocratic lava, we quote a " leucite basanite " from the Roman region. This is a melanocratic representative of our group of tephritic leucite-phonolites. The rock is described by H. S. Washington.

anorthite	13.1	olivine	15.9
leucite	17.3	ore	1.7
nepheline	3.4	apatite	0.6
augite	48.0	Colour index	(66)

Peralkaline Type.

A holocrystalline porphyritic rock containing large trapezohedral pseudomorphs, supposed to be derived from leucite, was described by J. F. Williams at Magnet Cove, Arkansas. The pseudomorphs consist of orthoclase, nepheline and cancrinite, the groundmass holds nepheline, orthoclase, pyroxene, garnet and biotite. Assuming that the pseudomorphs were originally leucite, H. S. Washington works out the composition of the rock as follows :—

orthoclase	3.9 (weight)	diopside and ægirine	19.2
leucite	36.9	melanite	14.5
nepheline	25.5	Colour index	(34)

H. S. Washington gave the name " italite " to an extremely leucite-rich lava of Mount Vesuvius. The composition of the rock is :—

leucite	90	ore	0.2
biotite	0.2	apatite	0.1
soda-diopside	4.0	glass	4.0
melanite	1.5	Colour index	(6)

The next two rocks are trachytic leucite-phonolites from the Roman region (Washington).

soda-orthoclase	71	(volume)	19.2
labradorite	—		7.0
leucite	14.4		37.0
nepheline	4.9		11.7
haüyne	0.1		10.0
soda-diopside	6.2		11.5
melanite	—		2.0
biotite	—		1.3
ore	2.4		—
apatite	—		0.3
Colour index	(9)		(15)

GROUP I. (b).

Soda-Syenoids and Soda-Phonolites.

These rocks contain a soda-felspathoid, which is generally nepheline but sometimes sodalite, cancrinite or analcime, without any leucite. In this group the tendency to sub-divide and to create specific names has been carried to extreme lengths, over forty names being in use for the eucrystalline varieties alone. Most of these names are unnecessary, and all lack quantitative definition.

It will be sufficient for our present purpose to divide the syenoids into two series, one in which felspar exceeds felspathoids, and another in which felspathoids exceed or entirely replace felspar. The characteristic members of the first series are leucocratic, and from the many names in use we select *foyaite* (derived from the typical locality at Foya, Portugal) as a generic name. For mesotype varieties of this series the name *malignite* (from Maligne River, Ontario) is suitable. Most examples of the second series are mesotype, and from their occurrence on a large scale at Ijo, Finland, they are known as *ijolite*, while the less common leucocratic varieties have received the name of *urtite* (Lujaur-Urt, Finland). When we consider the melanocratic syenoids, the separation of the more from the less felspathic varieties ceases to have much significance, for the light minerals form the minor part of the rock; the name *jacupirangite* (from Jacupiranga, Brazil) is therefore suitable for all such rocks, no matter what the proportion of felspar to felspathoid may be.

For the corresponding lavas there is less choice of names. *Phonolite* is currently used for the foyaitic lavas (both leucocratic and mesotype), and *nephelinite* for those of ijolitic composition.

Many lavas which have been described under the name of *nepheline basalt* have the same mineral composition as jacupirangite, so we shall employ the name provisionally in that sense. We have then the following classification of the soda-syenoids and soda-phonolites :—

Series I.—Felspar exceeds felspathoids	(a) Leucocratic (foyaite-phonolite).
	(b) Mesotype (malignite-phonolite).
	(c) Melanocratic (jacupirangite-nepheline basalt).
Series II.—Felspathoids exceed felspar	(b) Mesotype (ijolite-nephelinite).
	(a) Leucocratic (urtite-nephelinite).

Within these sub-groups it is possible to distinguish four chemical types, the peraluminous, metaluminous, subaluminous and peralkaline; but the majority of foyaites and malignites, and nearly all ijolites and urtites, are peralkaline.

Peraluminous Type.

The soda-syenoids of Ontario are mostly peraluminous, and some of them contain corundum. The felspar is always a very sodic variety, partly albite and partly soda-orthoclase or microperthite. P. D. Quensel has proposed to give the name " canadite " to all albite-rich foyaites, but since there is an excess of albite molecules over orthoclase molecules in nearly all foyaites, the distinction is not a very significant one. (It would be much more useful to make canadite a generic name for all peraluminous foyaites, to distinguish them from the commoner peralkine type.) Two analyses of the foyaites of Ontario are given below, after Adams and Barlow :—

	(1)	(2)
orthoclase	16.1	(weight) 4.4
albite	53.4	50.8
anorthite	1.3	1.2
nepheline	18.2	8.0
muscovite	8.0	—
biotite	1.3	29.6
ores	0.9	0.7
apatite	—	0.3
calcite	—	3.4
Colour index	(10)	(31)

Others of the Ontario syenoids have nepheline in large excess over felspar, and belong to the urtite division. The first of the following examples is from Craigmont (Adams and Barlow), the second from Monmouth (W. G. Foye) :—

	(1)	(2)
albite	—	9.2
oligoclase	29.7 (weight)	—
nepheline	63.2	56.7
scapolite	—	10.2
muscovite	4.4	—
biotite	0.5	22.5
corundum	0.5	—
rest	1.5	1.4
Colour index	(7)	(23)

The foyaites of Litchfield, Maine, and Salem, Massachusetts, are remarkably similar in composition, according to data furnished by W. S. Bayley and H. S. Washington respectively. The figures are

	Litchfield.	*Salem.*
orthoclase	27.0	27
albite	46.9	43
nepheline	17.0	20
cancrinite	2.0	1
biotite	6.9	6
accessory	—	3
Colour index	(7)	(9)

The peraluminous type of foyaite is also found in Ditró, Hungary, along with metaluminous and peralkaline types; but quantitative information is lacking as regards both the bulk and the composition of these types.

Peraluminous phonolite does not seem to have been described.

Metaluminous Type.

The " monmouthite " of Monmouth, Ontario, is a hornblende syenoid (urtite); it is much rarer than the mica syenoids of this region. The hornblende is a dark green variety with peculiar optical properties, called hastingsite; it carries about five per cent. of potash and soda, which raises the question whether this rock

ought not to be referred to the peralkaline type. The fact is that hastingsite and barkevikite are intermediate between common aluminous hornblende and the real soda-amphiboles, arfvedsonite, riebeckite and crocidolite, which have seven to twelve per cent. of alkalies and little or no alumina. Taking both alkalies and alumina into consideration, it seems that hastingsite and barkevikite are nearer to common hornblende (which nearly always holds two or three per cent. of alkalies) than to the soda-amphiboles.

The mode of typical "monmouthite" is as follows (Adams and Barlow):—

albite	1.8 (weight)	calcite	3.1
nepheline ...	72.2	hornblende	15.1
sodalite	0.3	hematite, etc.	0.6
cancrinite ...	5.1	Colour index	(16)

L. V. Pirsson and H. S. Washington describe hornblende-foyaite at Red Hill, New Hampshire. The hornblende is called catophorite, but it is evidently an aluminous hornblende with no excess of alkali, for acmite does not appear when the norm is calculated. It is stated that ægirine is sometimes present, but the modes and chemical analyses that are furnished are those of metaluminous rather than peralkaline rocks. The following modes are given:—

	(1)	(2)
orthoclase	36	32
albite	37	43
nepheline	14	7
sodalite	5	2
hornblende	7	12
accessory	1	4
Colour index	(8)	(16)

Coming now to rocks with a higher colour index, we note the following instances of mesotype hornblende syenoid in Ontario. The first is malignite from Monmouth (Adams and Barlow), the second is an ijolite from Tory Hill, which carries a brown hornblende, a green pyroxene, and a red garnet (W. G. Foye).

	(1)	(2)
orthoclase	2.8 (weight)	—
albite	22.3	7
anorthite	1.7	—
nepheline	26.2	30
hornblende	39.7	30
diopside	—	20
garnet	—	7.5
calcite	5.5	5.0
apatite	0.3	0.5
Colour index	(40)	(58)

A few syenoids contain a lime-iron garnet without the soda-pyroxene that usually accompanies it; they are therefore placed in this group. The " borolanite " of J. Horne and J. J. H. Teall, from Assynt, Scotland, is a melanite-biotite syenoid which typically holds no pyroxene at all. The rock exhibits white spots, of rounded or rudely polygonal outline, which appear to have been formed by the alteration of some unknown mineral (see " pseudo-leucite, p. 243), set in a base of alkali-felspar, melanite and biotite. The white spots consist of felspar and zeolites, and the mode of the rock is as follows (S. J. S.) :—

felspar, etc., of white spots	33.7 (volume)
felspar, etc., of groundmass	32.6
melanite, sphene	25.5
biotite	8.2
Colour index	(34)

Teall also described a simple melanite-biotite foyaite from the same district, consisting of orthoclase 74, nepheline 20, melanite 3.1, biotite 3 per cent. by volume (Colour index 6).

A darker rock of this type was found by R. A. Daly in the Kruger Mountain area, British Columbia, having the following mode :—

soda-potash-felspar	63.9 (volume)	melanite	8.8
nepheline	15.1	apatite	0.6
biotite	11.1	sphene, ore	0.5
		Colour index	(21)

An ijolite containing 14 per cent. of melanite (schorlomite) along with a non-alkaline pyroxene, occurs at Ice River, British Columbia (J. A. Allan), and a still greater content of melanite and schorlomite is shown by a jacupirangite of Magnet Cove, Arkansas. The mode given by H. H. Washington is

orthoclase	4.8	melanite, schorlomite	29.7
nepheline	24.1	magnetite	3.6
biotite	6.2	apatite	1.0
diopside	30.6	Colour index	(71)

Melanocratic hornblende syenoid (jacupirangite) is described by G. I. Finlay at Tamaulipas, Mexico. The following modes are given :—

	(1)	(2)
orthoclase	12	5.6
nepheline	18	13.2
biotite	—	2.2
hornblende	40	60.5
titanaugite	23	13.9
sphene	2	2.8
magnetite	2.7	0.4
apatite	1.2	1.4
Colour index	(69)	(81)

An ultra-melanocratic rock is the jacupirangite of Magnet Cove, Arkansas, described by H. S. Washington. This rock holds only 4 per cent. of nepheline, with 79 per cent. of non-sodic pyroxene, 5 of biotite, 8.7 of magnetite, and traces of pyrite and calcite. The colour index is about 93.

The " okaite ", described by J. Stansfield, from the Oka Hills, Quebec, is one of the rare deep-seated rocks that contain melilite. The following mode is given :—

haüyne	21	perovskite	6
melilite	52.5	magnetite	7.5
biotite	8	pyrites	0.5
calcite	2	apatite	2.5
		Colour index	(77)

Quantitative descriptions of metaluminous *phonolite* are very scarce. The " vulsinite " of H. S. Washington, from Italy, is an augite-biotite phonolite. The composition of two examples of this rock is as follows :—

soda-orthoclase	65.2 (weight)	52.1
labradorite	14.3	17.8
nepheline	5.4	7.8
biotite	3.2	1.7
augite	8.3	17.7
magnetite	3.3	2.4
apatite	0.3	0.5
Colour index	(15)	(22)

The following highly melanocratic lavas are *nepheline basalts,* one without and one with melilite. The former is from Fort Hall Reservation, Texas, and it has been described by Mansfield and Larsen. The latter was described by C. S. Ross, at Winnett, Montana.

	(1)	(2)
nepheline	20 (weight)	15 (volume?)
haüyne	—	
biotite	8	16
pyroxene	39	5
olivine	26	35
melilite	—	17
ore	4	6
apatite	1	1
groundmass	—	4
Colour index	(78)	(80)

Subaluminous Type.

Subaluminous rocks are rare in this class, for the pyroxene tends to be mantled with ægirine, so taking the rock into the peralkaline type.

The " Arroyo Grande " type of the foyaite of Tamaulipas, Mexico, contains a little augite as its only dark silicate. According to G. I. Finlay the mode is

orthoclase	60 (volume?)	augite	1
albite	5	sphene	0.7
nepheline	25	magnetite	8
		Colour index	(10)

V. Hackman describes a pegmatitic ijolite at Kuolajärvi, Finland, which has common diopside as its only dark silicate. The mode is

nepheline	30.4 (weight)	magnetite	8.0
cancrinite	17.2	apatite	3.1
diopside	41.0	sphene	0.3
		Colour index	(52)

Among lavas, the phonolite of Leeuwkraal, Transvaal, is a pure subaluminous type. It contains

microperthite	75	diopside	10
nepheline	10	titanomagnetite	2
sodalite	10	sphene	1
		Colour index	(13)

A curious lava described by R. A. Daly in British Columbia, under the name "shackanite," is an analcime-phonolite. It consists of

anorthoclase	33.5	olivine	2.6
analcime	29.2	magnetite	2.0
biotite	0.2	apatite, sphene	2.0
augite	5.5	glass	25.0

Some nepheline basalts are subaluminous. B. Koto has described a nepheline basalt at Yinge-men, Manchuria, which holds 30 per cent. (by volume) of nepheline, 15 of olivine, and apparently about 50 per cent. of augite, since the only other constituent mentioned is a little glass. The colour index must consequently be near 65.

H. G. Backlund has given the mode of a nepheline basalt from General Vilkitzky Island, in the Arctic Ocean. It is

nepheline	32.1	magnetite	10.1
olivine, augite	55.5	apatite, perovskite	2.3
		Colour index	(68)

Peralkaline Type.

The great majority of syenoids, and many phonolites, are of this type. The three greatest masses of nepheline rocks in the world (Kola, Julianehaab, and Pilansberg) consist almost exclusively of peralkaline types; and other large syenoid intrusions such as those of Serra de Monchique, Arkansas, Cabo Frio, Serra de Tinguá, and Los Islands are mainly peralkaline.

Foyaites with only small quantities of nepheline or sodalite, which are near syenite in composition, are sometimes called

" pulaskite," from their occurrence in Pulaski County, Arkansas. H. S. Washington gives the following analyses of the pulaskite of Fourche Mountain :—

	(1)	(2)
orthoclase	28.6	35.1
albite	39.0	39.8
nepheline	6.2	3.1
sodalite, nosean	1.2	1.2
ægirine	6.9	5.1
biotite	7.9	
hornblende	—	11.0
diopside	—	
apatite	—	0.5
sphene	2.7	—
rest	9.5	4.2
Colour index	(17)	(17)

The " hedrumite " of W. C. Brögger, from Hedrum, Norway, is not in any essential respect different from pulaskite, and the " sölvsbergite " of Tjose-Aklungen is a fine-grained dyke rock with trachytic texture, consisting of alkaline felspar 71.5, nepheline 5, soda-pyroxene 15.2, biotite 7.1, melanite 0.7 and perovskite 0.3 per cent.

The " laurdalite " of Brögger is only distinguished from other foyaites by the peculiar rhombic habit of the felspar (anorthoclase). The mode is as follows :—

orthoclase	19.0	soda-pyroxene	8.3
albite	40.6 (62.3)	biotite	9.5
anorthite	2.7	ore	2.8
nepheline	13.0	apatite, zircon	1.7
sodalite	2.0	Colour index	(22)

The foyaite of Brathagen, Norway, is compared below with a foyaite from Alnö, Sweden (A. G. Högbom), and one from Cevadaes, Portugal (A. Osann).

	Brathagen	*Alnö*	*Cevadaes*
orthoclase & perthite	55.2	56	65.5
nepheline	27.4	25	25.5
sodalite, cancrinite	8.3	—	1.0
soda-pyroxene	4.7	14	7.0
biotite	2.5	—	—
ore, apatite, etc.	1.6	3	1.0
Colour index	(9)	(17)	(8)

The foyaites of Franspoort and Leeuwkraal, Transvaal, are very close to the last three in composition (S. J. S.).

	(1)	(2)
soda-orthoclase, perthite	55	60
nepheline, analcime	33	25
sodalite	2.5	3
soda-pyroxene	8.5	10
sphene	0.5	1
ore		.1
Colour index	(10)	(12)

The foyaite of Leeuwfontein, Transvaal, is so rich in felspathoids as almost to fall in the urtite group. It carries 46 per cent. of felspar (by volume), with 45 of nepheline and sodalite, and 9 of ægirine, with which a little arfvedsonite is included.

A remarkable rock which J. Morozewicz named "mariupolite," from its occurrence in the Mariupol district of Russia, is an albite foyaite containing twenty-four times as much soda as potash. The mode is albite 74, nepheline 13, ægirine 7.5, biotite 4, zircon 2 per cent.

"Lujaurite" is the name given by W. Ramsay to foyaites of Lujaur-Urt, in the Kola peninsula, which are characterised by the presence of a considerable quantity of ægirine needles arranged in parallel position, giving the rock the appearance and texture of a crystalline schist. These rocks contain 45 to 50 per cent. of felspar, 22 to 27 of nepheline, and 23 to 30 of ægirine, together with a variable and often large proportion of eudialyte.

Among dyke-foyaites, the Tingua type (tinguaite), which takes its name from the Serra de Tingua in Brazil, differs from the Lujaur type only by being more fine-grained. The following analyses are of tinguaites from (1) Judith Mountains, Montana (Weed and Pirsson); (2) Serra de Monchique, Portugal (Kraatz-Koschlau and Hackmann); (3) Hedrum, Norway (W. C. Brögger); (4) Fen district, Norway (W. C. Brögger); (5) Bear-paw Mountains, Montana (Weed and Pirsson).

	(1)	(2)	(3)	(4)	(5)
orthoclase	54.6	20	20.5	25.3	44.4
albite	18.8	40	30	5.9	12.1
nepheline	8.8	20	30	33.6	9.3
sodalite, cancrinite	1.2	—	—	5.1	—
soda-pyroxene	12.8	8	15.2	28.6	34.2
biotite	—	3.5	2.5	—	—
ore, etc.	—	3	—	1.3	—
Colour index	(13)	(18)	(18)	(29)	(34)

As an example of a mesotype foyaite or *malignite*, we quote A. C. Lawson's analysis of the original malignite of Poohbah Lake (Maligne River), Ontario :—

orthoclase	20.9	soda-diopside	48.2
nepheline	19.6	sphene	1.0
biotite	2.0	apatite	5.8
		Colour index	(57)

The " covite " of H. S. Washington is a hornblende malignite occurring at Magnet Cove, Arkansas. It contains

orthoclase	29.3	hornblende	18.8
albite	22.8	magnetite	2.5
nepheline	9.0	sphene	3.1
soda-diopside	13.5	apatite	1.0
		Colour index	(39)

A malignite described by R. A. Daly at Kruger Mountain, British Columbia, contains melanite. The mode is

soda-orthoclase, perthite,	36.3 (volume)	melanite	9.5
nepheline	5.4	apatite	1.0
biotite	11.0	magnetite, sphene	0.3
soda-diopside	36.5	Colour index	(58)

Cancrinite is very often present in rocks that contain nepheline, and at times it is so abundant as to be a major constituent of the rock. W. Ramsay and E. T. Nyholm described a rock at Kuolajärvi, Finland, which carries 29 per cent. of cancrinite, along with nepheline, orthoclase, ægirine and accessories. The foyaite of Diamond Jo quarry, Magnet Cove, also holds much cancrinite. H. S. Washington gives the following data :—

orthoclase	51.8	soda-pyroxene	14.3
nepheline	20.3	sphene, pyrite	0.5
cancrinite	13.1	Colour index	(15)

There is also a group of analcime-syenoids, in which analcime generally displaces nepheline entirely. Two such rocks have been described by G. W. Tyrrell, in the west of Scotland.

	(1)	(2)
alkali-felspar	66.8	54.7
plagioclase	—	5.2
analcime	15.9	8.1
ægirine	9.3	3.3
titanaugite	—	15.1
soda-hornblende	4.3	1.6
olivine	—	2.6
ore	2.5	7.9
apatite	1.2	1.5
Colour index	(17)	(32)

Tinguaites with a very high content of analcime have been described by C. H. Clapp in Massachusetts. The modes are :—

alkali-felspar	43 (volume)	38.2
nepheline	—	10.9
analcime	40	37.4
ægirine	15	13.5
ore	2	—
Colour index	(17)	(14)

A most unusual variety is the " blairmorite " of J. D. MacKenzie from Alberta, Canada. This is a porphyritic rock with insets of analcime in a groundmass of foyaitic composition. The mode is

orthoclase	4 (weight)	soda-diopside	14
nepheline	5	sphene	0.5
analcime	71	secondary	5
melanite	1	Colour index	(17)

Coming next to rocks in which felspathoids exceed felspar, we must notice first the *urtite* of Lujaur-Urt, Finland. W. Ramsay has given the composition of two of these rocks, as follows :—

nepheline	86 (weight)	82
ægirine	12	16
apatite	2	2
Colour index	(14)	(18)

Urtite has also been recorded at Kuusamo, Finland (V. Hackmann), and at Monmouth, Ontario (Adams and Barlow). Both varieties contain felspar.

In the following instances sodalite is very abundant. The rocks referred to are (1) a nepheline porphyry from Norway (W. C. Brögger); (2) the " sodalite foyaite " of St. Hilaire Mountain, Quebec (J. J. O'Neill).

	(1)	(2)
alkali-felspar	40.6	32.6
nepheline	32.6	34.8
sodalite	11.0	17.5
soda-pyroxene	8.0	11.0
biotite	5.6	—
eudialyte	—	4.0
sphene, ore, apatite	3.8	—
Colour index	(17)	(15)

An extremely high content of sodalite (20 to 50 per cent.) is present in some of the sodalite foyaites of Greenland (N. V. Ussing); while in the sodalite foyaite of St. Hilaire Mountain, Quebec, J. J. O'Neill records 70 per cent. of sodalite.

The mesotype *ijolites* are commoner than the urtites, although they remain very rare rocks. The first ijolite was recognised and named at Ijo, in the Kuusamo district of Finland, by W. Ramsay and H. Berghell. It is compared below with the remarkably similar ijolite of Sekukuniland, Transvaal (2) (S. J. S.). Both rocks locally carry large quantities of titaniferous melanite. The first analysis is by V. Hackmann.

	(1)	(2)
nepheline	51.6 (volume)	54.6 (volume)
cancrinite	—	7.4
calcite	—	0.5
soda-pyroxene	39.2	32.2
sphene	2.1	0.5
melanite	0.7	—
apatite	4.3	4.8
ore, etc.	—	—
Colour index	(46)	(38)

The ijolite of Umptek, Kola Peninsula, is compared below with that of Magnet Cove, Arkansas. The presence of 15 per cent. of melanite in the latter rock bears witness to its proximity to a limestone contact. The first analysis is by T. Brenner, the second by H. S. Washington.

	Umptek	*Magnet Cove*
nepheline	38.2	38.7
soda-pyroxene	16.2	42.8
soda-hornblende	32.0	—
melanite	—	15.3
mosandrite	3.8	—
sphene	5.8	—
magnetite	2.4	—
apatite	1.6	3.0
Colour index	(62)	(61)

W. C. Brögger has described beautiful examples of ijolite in the Fen district of Norway; they occur, as usual, in close proximity to limestone. Brögger has introduced the name "melteigite" for these rocks, but they are similar in every respect to the original Kuusamo ijolite, and no new name is needed. The following modes are characteristic:—

nepheline (and decomposition products)	52	47.3
soda-pyroxene	27.5	27.2
melanite	3.4	18.0
biotite	5.5	—
sphene	3.0	2.0
apatite	1.7	1.5
ore	3.8	1.9
calcite, etc.	3.5	0.2
Colour index	(46)	(51)

The following analyses are of melanocratic syenoids (jacupirangites). The first is from Gunnison County, Colorado, the second from the Fen district of Norway. Both are given by W. C. Brögger.

	(1)	(2)
nepheline, cancrinite, etc.	26.7	30.2
soda-pyroxene	52.3	51.9
biotite	5.1	—
sphene	—	3.7
perovskite	4.7	—
melanite	—	0.9
apatite	5.9	4.4
ore, etc.	5.0	9.0
Colour index	(73)	(75)

Among *phonolites* of peralkaline type, few have been described in quantitative terms. H. S. Washington gives the modes of two phonolites from the Roman region, as follows :—

	(1)	(2)
soda-orthoclase	84.6 (weight)	82.7 (weight)
nepheline	3.7	5.4
sodalite, haüyne	3.9	2.1
soda-diopside	3.8	4.5
sphene	—	0.6
ore	4.0	4.2
Colour index	(8)	(9)

An analcime-rich phonolite is described by A. MacGregor near Haddington, Scotland, containing

orthoclase	37.6	sodalite	2.7
albite	20.1	soda-diopside	5.7
anorthite	3.2	olivine	1.8
nepheline	4.2	ore, etc.	4.1
analcime	20.5	Colour index	(12)

An almost mesotype phonolite, in Mozambique, E. Africa, is described by A. Holmes. The mode is

anorthoclase	33.8	soda-amphiboles	15.8
nepheline, zeolites	31.3	ore	2.0
soda-pyroxene	15.1	calcite	2.0
		Colour index (33, weight)	

GROUP II.

Dioroids, Gabbroids, etc.

In this group we place rocks which contain more anorthite than the sum of the orthoclase and leucite present. No instance is known to the writer of a leucite rock that satisfies this definition, so our illustrations must all be drawn from the nepheline and analcime rocks. Since the number of rocks that fall into this group is small, it will be sufficient to distinguish two instead of three facies on the basis of the colour index. We shall therefore give the name *dioroid* (or *essexite*) to rocks with less than 50 per cent. of heavy minerals, and *gabbroid* (or *theralite*) to those with a colour index greater than 50. The names *tephrite* and *basanite* might be given to the corresponding lavas, of which, however, scarcely any quantitative descriptions are available.

(1) Dioroids (Essexites) and Tephrites.

The " dungannonite " of Ontario is a peraluminous dioroid. Adams and Barlow supply the following mode :—

andesine (Ab_3An_2)	72	corundum	13.2
nepheline	3	biotite	5
scapolite	2	muscovite	3
calcite	0.4	magnetite	1.4
		Colour index	(23)

The " raglanite " of the same region holds 69 per cent. of oligoclase, 12 of nepheline, and 4.5 of corundum, with muscovite, biotite, magnetite, calcite and apatite.

The typical examples of essexite are metaluminous. The name was first given to a rock in Essex Co., Massachusetts, which, in H. S. Washington's words, is " composed essentially of augite, hornblende, biotite and plagioclase, with subordinate orthoclase, nepheline and sodalite." The felspar in this rock is mostly labradorite, with some microperthite and microcline, and the nepheline is interstitial to it.

The essexite of Rongstock, Bohemia, contains a plagioclase with zonal structure, the cores being Ab_1An_1, and the mantles oligoclase or orthoclase. J. E. Hibsch gives the following data :—

orthoclase	10	biotite	8
albite	25	augite	30
anorthite	18	hornblende	4
cancrinite	2	magnetite	3
		Colour index	(45)

Rocks of this type occur in the Monteregian Hills of Quebec, for example in St. Hilaire Mountain (modes 1 and 2, by J. J. O'Neill) and also in Mount Yamaska (3, by G. A. Young).

	(1)	(2)	(3)
soda-orthoclase	—	—	15.0 (volume)
labradorite	55.0 (volume)	48.7 (weight)	31.5
nepheline	4.5	3.9	7.5
biotite	5.5	5.3	1.0
hornblende	6.0	6.7	26.0
augite	19.0	21.4	4.0
olivine	1.5	1.6	—
sphene	0.5	0.6	6.5
ore	5.0	8.6	5.0
apatite	3.0	3.2	1.5
Colour index	(40)	(47)	(45)

Entirely similar rocks have been described by A. Lacroix from Madagascar and Tahiti, but unfortunately the modes are not given.

G. W. Tyrrell has described under the name " lugarite " certain rocks from the west of Scotland which differ from normal essexite mainly by the presence of a large proportion of analcime. The following modes are given :—

	(1)	(2)
plagioclase	10.5	14.6
nepheline + analcime	42.5	49.0
augite	21.7	—
hornblende	17.2	29.5
ore	5.0	2.7
apatite	3.1	4.2
Colour index	(47)	(36)

Scarcely any lavas are available for quotation here. The analcime-basalts of Sardinia, which were formerly mistaken for leucite-basalts, fall near the boundary between essexite and theralite. The following modes are furnished by H. S. Washington :—

	(1)	(2)	(3)
analcime	8	5	10
biotite	—	5	—
augite	20	20	25
olivine	2	6	10
magnetite	15	18	13
apatite	3	2	2
glass	42	44	40
Colour index	(40)	(51)	(50)

The glass, in the first two of these rocks, has the composition of labradorite; in the third, it corresponds to a mixture of orthoclase 15, labradorite 20, and analcime 5 per cent.

(2) Gabbroids (Theralites) and Basanites.

The typical theralite is that of Duppau, Bohemia, which has not yet been described in quantitative terms. F. Bauer states that the dark minerals (augite, hornblende, biotite, olivine and accessories) predominate over the light ones (nepheline, plagioclase, orthoclase). The nepheline is abundant, but interstitial, and plagioclase exceeds orthoclase.

W. Ramsay and T. Brenner have described theralites from Umptek, Kola Peninsula. The principal dark minerals are augite, hornblende, olivine and biotite, which make up from two-thirds to three-fourths of the rock; the light minerals are plagioclase, a little orthoclase or microcline, nepheline and sodalite.

J. E. Wolff described typical theralite from Costa Rica, unfortunately without giving quantitative details. Augite, olivine and biotite are the dark minerals, the felspar is labradorite with a little orthoclase; and nepheline and sodalite are both present.

G. W. Tyrrell records rocks belonging to this interesting and scarce type in the West of Scotland. The two analyses given below are those of theralites from Lugar, Ayrshire.

labradorite	23.3	16.4
nepheline	12.6	16.6
biotite	3.6	6.7
hornblende	—	12.2
augite	36.1	35.9
olivine	18.6	8.7
ore	4.2	2.5
apatite	1.6	1.0
Colour index	(64)	(67)

Another Scottish rock, the "essexite" of Crawfordjohn, is a theralite in our sense of the term. It is subaluminous, no more than a trace of biotite being present. The following modes of the normal rock (1) and an augite-rich facies (2) are given by A. Scott.

	(1)	(2)
orthoclase, labradorite	32.2	30.9
nepheline	7.1	4.6
analcime	5.9	5.2
biotite	0.3	0.4
augite	27.4	41.0
olivine	23.8	13.8
ore	2.3	2.9
apatite	1.0	1.2
Colour index	(55)	(59)

A metaluminous theralite was described by G. W. Tyrrell at Barshaw, in the west of Scotland. Orthoclase, plagioclase, nepheline and analcime make up 30.7 per cent. of this rock, and the dark minerals are augite 29.8, hornblende 14.7, olivine 18.6, ore 4.9, and apatite 1.1 per cent. (Colour index 69.)

Other theralites occur in the Kyle district of Argyllshire. The proportion of biotite is so small that the rocks are virtually subaluminous. The following modes are given by Tyrrell:—

	(1)	(2)	(3)	(4)
labradorite	26.8	33.1	32.3	17.0
nepheline	3.8	2.3	6.1	—
analcime	1.8	0.6	1.4	4.7
biotite	2.0	1.8	1.4	—
augite	25.1	27.6	25.9	19.7
olivine	37.8	29.5	27.9	55.4
ilmenite	2.1	4.4	4.3	2.5
apatite	0.6	0.7	0.7	0.7
Colour index	(68)	(64)	(60)	(78)

An olivine-theralite from the Austral Islands, in the Pacific Ocean, which has been described by W. Campbell Smith, closely resembles these Scottish examples. The mode of this rock is:—

orthoclase	5.5	augite	36.5
albite	5.2	olivine	24.4
anorthite	8.3	iron ores	6.0
nepheline	11.7	apatite	1.3
		Colour index	(68)

Some of the "teschenites" (analcime-dolerites) of the west of Scotland fall here. The modes are again by G. W. Tyrrell.

orthoclase	10.2	—	—
labradorite	23.2	28.9	6.6
analcime	16.1	13.8	12.2
biotite	3.4	2.9	3.7
hornblende	—	—	18.1
augite	28.1	39.9	24.0
olivine	10.6	4.6	32.5
ore	7.1	9.9	1.9
apatite	1.3	—	1.0
Colour index	(50)	(57)	(81)

REFERENCES.

Adams, F. D. and Barlow, A. E.—Canada, Geol. Survey, Mem. 6, 1910.
Allan, J. A.—Canada, Geol. Survey, Mem. 55, 1914.
Backlund, H. G.—Bull. Acad. Imp. Sci., Petrograd, 1915, *289*
Bauer, F.—Tschermak's Min. Pet. Mitt., 1903, *266*.
Bayley, W. S.—Bull. Geol. Soc. America, 1892, *231*.

Brenner, T.—Comm. geol. Finlande, Bull. 52, 1920.
Brögger, W. C.—Eruptivgesteine des Kristianiagebietes, vol. 1, 1894; vol. 2, 1895; vol. 3, 1898; vol. 4 (Fen district), 1921.
Clapp, C. H.—U.S. Geol. Survey, Bull. 704, *106*.
Cross, W.—Amer. Jour. Sci., 1897, *115*.
Daly, R. A.—Canada, Geol. Survey, Mem. 38, 1912, *411, 448*.
Finlay, G. I.—Ann. New York Acad. Sci., 1904, *247*.
Foye, W. G.—Amer. Jour. Sci., 1915, *413*.
Hackmann, V.—Comm. geol. Finlande, Bull. 11, 1920 (Kuusamo).
Hibsch, J. E.—Tschermak's Min. Pet. Mitt., 1902, *157*; 1899, *1*.
Högbom, A. G.—Sveriges Geologiska Undersökning, no. 148, 1895.
Horne, J. and Teall, J. J. H.—Trans. Roy. Soc. Edinburgh, 1892, *163*. (See also Shand, S. J., 1910.)
Holmes, A.—Quart. Jour. Geol. Society, 1917, *222*.
Koto, B.—Jour. Coll. Sci. Imp. Univ. Tokyo, 1912, *1*.
Kraatz-Koschlau, K. and Hackmann, V. — Tschermak's Min. Pet. Mitt., 1896, *197*.
Lacroix, A.—(Madagascar) Mineralogie de Madagascar, vol. II., *628*.
do. —(Tahiti) Bull. Soc. Geol. France, 1910, *97*.
Lawson, A. C.—Univ. of California, Bull. Dept. Geol., vol. I., 1896, *337*.
Macgregor, A. G.—Geol. Magazine, 1922, *514*.
MacKenzie, J. D.—Canada, Geol. Survey, Museum Bull. 4, 1914.
Mansfield, G. R. and Larsen, E. S.—Jour. Washington Acad. Sci., 1915, *463*.
Morozewicz, J.—Tschermak's Min. Pet. Mitt., 1902, *238*.
O'Neill, J. J.—Canada, Geol. Survey, Mem. 43, 1914.
Osann, A.—Neues Jahrb. Min., 1907, *109*.
Ramsay, W.—Fennia, vol. 15, no. 2, 1899.
do. —Geol. Fören. Förhandl., Stockholm, 1896, *459*.
do. and Berghell, H.—Geol. Fören. Förhandl., Stockholm, 1891, *300*.
do. and Hackman, V.—Fennia, Vol. II., no. 2, 1894.
do. and Nyholm, E. T.—Comm. Geol. Finlande, Bull. 1, 1895.
Ross, C. S.—Amer. Jour. Sci., 1926, *219*.
Scott, A.—Geol. Magazine, 1915, *455, 513*.
Shand, S. J.—(Scotland) Trans. Edinburgh Geol. Soc., 1910, *376*.
do. —(Transvaal) Trans. Geol. Soc. S. Africa, 1921, *111*; 1921, *232*; 1922, *81*.
Smith, W. C.—Quart. Jour. Geol. Soc., 1927.
Stansfield, J.—Geol. Magazine, 1923, *443*.
Teall, J. J. H.—Geol. Magazine, 1900, *386*. (See also Shand, S. J., 1910.)
Tyrrell, G. W.—Geol. Magazine, 1912, *69*; 1915, *304*; 1923, *249*.
do. —Quart. Jour. Geol. Soc., 1917, *84*.
Ussing, N. V.—Meddelelser om Grönland, Copenhagen, 1912.
Washington, H. S.—(Rome) Carnegie Inst. Washington, pub. 57, 1906.
do. —(Essex Co.) Jour. Geol. 1898, *787*, 1899, *35*, etc.
do. —(Magnet Cove) Jour. Geol., 1901, *607*.
do. —(Italite) Amer. Jour. Sci., 1920, *33*.
do. (Sardinia) Jour. Geol. 1914, *742*.
Weed, W. H. and Pirsson, L. V.—(Missourite) Amer. Jour. Sci., 1896, *315*.

Weed, W. H. and Pirsson, L. V.—(Judith Mts.) U.S. Geol. Survey, Ann. Rep. 18, *437*.
do. (Bearpaw Mts.) Amer. Jour. Sci., 1896, *136*.
Williams, J. F.—Arkansas, Geol. Survey, Ann. Rep., 1890.
Wolff, J. E.—Amer. Jour. Sci., 1896, *271*.
Young, G. A.—Canada, Geol. Survey, Ann. Rep., 1906, part H.

CHAPTER XV.

METEORITES.

The greatest weakness of petrography, as a method of investigating the composition of the earth, is that direct observations can only be made upon rocks that have crystallised within a few thousand feet from the surface, say a thousandth part of the earth's radius. There is good reason, no less on petrological than on geophysical and astronomical grounds, to suppose that the matter that forms the interior of the planet is different in many respects from surface rocks; but direct observation of this matter is naturally impossible. It is here that meteorites come to our assistance. It is quite immaterial what view one holds regarding the origin of meteorites. Astronomy, supported by the spectroscope, has shown that the universe is formed of the same elementary materials throughout; so whether one regards meteorites as shattered stars or shattered planets, nebular knots or condensed comets, as bolts from the sun or as bombs from terrestial volcanoes, the important fact for us is that *meteorites bring to our notice a type of rock existing in the solar system but different from anything that occurs in the outer shell of our planet;* and this material has just the sort of composition that petrology, geophysics and astronomy combine to indicate as likely to be found in the interior of the earth. For this reason, the study of meteorites has an extraordinary interest for the petrologist, and no discussion of eruptive rocks can be complete which ignores this fascinating aspect of the subject.

Meteorites show their relationship with the more familiar eruptive rocks in many ways. Most of the constituents of meteorites, though not all, are identical with common rock-forming minerals, and they show the same crystalline habit as these. The textures of meteorites are partly similar to those of eruptive rocks and partly different; but the differences between meteorites and terrestial lavas are not more striking than those between lavas

and plutonic rocks, or lavas and tuffs. On the other hand, meteorites have scarcely any characters in common with sedimentary rocks or crystalline schists.

The Chemistry of Meteorites.

The abundant chemical elements in eruptive rocks are oxygen, silicon, aluminium, iron, calcium, sodium, potassium, magnesium, and titanium, in that order, with hydrogen and sulphur occasionally rising to prominence. (See the table on page 29.)

The common elements in the iron meteorites are iron and nickel, with small quantities of cobalt, manganese and copper. The elements of the stony meteorites (disregarding admixed grains of nickel-iron) occur in the following order of abundance, according to a computation by G. P. Merrill :—oxygen, silicon, magnesium, iron, aluminium, calcium, sodium, chromium, manganese, potassium.

There is a difficulty about combining these statements into a conclusion that could be applied to all meteorites. Stony meteorites fall much more numerously than iron ones, but owing to their brittle character they tend to be dissipated in the form of small fragments and dust and so to escape notice. The largest known mass of meteoric stone reached the earth as a mass of only 1,200 lbs. in weight. Again, the similarity of meteoric stones to many terrestial rocks makes their discovery largely a matter of accident. The iron meteorites, on the other hand, are comparatively big. The Cape York iron, from Greenland, is eleven feet long and weighs over 36 tons. Even this is reduced to insignificance by a mass of iron recently discovered in the Adrar desert, West Africa, and identified as a meteorite by A. Lacroix; it is said to be a hundred metres long and forty metres high. Even a small lump of iron is more likely to attract notice than a lump of stone; thus it is certain that no comparison of irons and stones, either by number or by weight, can give a trustworthy basis for computing the relative abundance of the chemical elements in the irons and the stones combined. W. A. Wahl holds that the order of abundance is approximately as follows :—iron, oxygen, silicon, magnesium, aluminium, calcium, nickel, sodium, sulphur, potassium, cobalt, phosphorus, carbon and hydrogen.

By adding together all the reliable chemical analyses that have been made, without taking weights into account at all, O. C. Farrington has formed the following estimate of the average composition of meteorites :—

iron	72.06	aluminium	.39
oxygen	10.10	sodium	.17
nickel	6.50	phosphorus	.14
silicon	5.20	chromium	.09
magnesium	3.80	potassium	.04
sulphur	.49	carbon	.04
calcium	.46	manganese	.03
cobalt	.44	other elements	.05

In addition to those named, a number of other elements have been detected in very small quantity; such are chlorine, copper, tin, titanium, vanadium, the metals of the platinum group, and the inert gases. No element has been found in meteorites that was not already known on the earth; on the other hand, some of the comparatively common elements have not yet been detected in meteorites. Of these fluorine is the most conspicuous example; while the almost total absence of the strongly radioactive elements from meteorites is a point of some significance.

Elements which occur in the native, or uncombined, state are iron, nickel, cobalt and carbon, commonly; manganese, copper, hydrogen, nitrogen and other gases, and the platinum group of metals, in traces. Copper is a very scanty component of most meteoric irons, but the Richardton stone exhibits specks of native copper. The platinum metals reach the unusual proportion of one ounce to every five tons of iron in the Cañon Diablo meteorites of Arizona. The presence of native phosphorus in the Saline stone, Kansas, was announced by O. C. Farrington.

W. A. Wahl has pointed out that the elements which are found in the native state are those whose oxides have a low heat of formation, as the following table shows :—

$Mg + O = MgO + 145.8$ cal.	$Mn + O = MnO + 90.8$ cal.
$Ca + O = CaO + 131.3$ „	$C + O = CO + 68.2$ „
$Al_2 + O_3 = Al_2O_3 + (3 \times 131.2)$ „	$Fe + O = FeO + 64.6$ „
$Na_2 + O = Na_2O + 100.2$ „	$Co + O = CoO + 63.8$ „
$K_2 + O = K_2O + 97.1$ „	$Ni + O = NiO + 59.7$ „
$Si + O_2 = SiO_2 + (2 \times 90.9)$ „	$Cu_2 + O = Cu_2O + 43.8$ „

Each element in this list is able to reduce the oxides of those which follow it in the list; thus no iron can become oxidised until all the sodium is in the form of the oxide; no nickel, until all the iron has been oxidised, and so on. This leads directly to a con-

clusion that has been established by G. T. Prior, that in meteoric stones generally, the poorer they are in nickel-iron, the richer that iron is in nickel, and the richer in iron are the magnesium silicates.

The Mineralogy of Meteorites.

The minerals of meteorites may be discussed in two groups, as follows :—

(1) Minerals which occur in terrestial eruptive rocks;

(2) Minerals which have not been found in terrestial rocks.

The common minerals of group (1) are olivine, ortho-pyroxenes, clino-pyroxenes (generally rather poor in lime and nearly free from alumina), plagioclase felspars ranging from anorthite to oligoclase, chromite, and pyrrhotite (including the variety troilite). The less common minerals of this group are quartz, which has been found in the St. Marks stone as well as in several irons; tridymite, graphite, magnetite, chlor-apatite, various hydrocarbons, and some soluble salts such as NaCl. Minute diamonds have been identified in Cañon Diablo iron, and a red spinel was reported by W. M. Foote in the Holbrook stones.

The chief members of group (2) are the alloys of iron with nickel, including a little cobalt, manganese and copper. When a polished surface of an iron meteorite is treated with a suitable etching reagent, a peculiar structure is often revealed which shows that the iron is built up of intersecting plates of at least two materials, differing in colour and in resistance to acids, while a third material fills the angular interstices. The broader plates, which are more readily attacked by acids, consist of an alloy called *kamacite*, having the approximate composition Fe 93 per cent., Ni(+Co) 7 per cent. Narrower plates, the edges of which stand out in relief on the etched surface, are composed of *taenite*, another alloy containing from 14 to nearly 50 per cent. of nickel (and cobalt); this alloy is much less abundant than kamacite and is sometimes entirely absent. The material which fills the interspaces is called plessite; it is intermediate in composition between kamacite and tanite, and it is perhaps just a microcrystalline aggregate of these two alloys.

Alloys of iron and nickel are not entirely unknown in terrestial rocks. Masses of iron containing one to two per cent. of nickel have been found in basalt on Disko Island, West Greenland, and grains of nickeliferous iron have been found in gravels derived from serpentines and peridotites in New Zealand and elsewhere;

but these irons differ both in structure and in composition from iron of known meteorites.

Other minerals which occur in meteorites, but not in eruptive rocks, are *lawrenceite* (ferrous chloride, containing a little nickel); *cohenite,* a carbide of iron and nickel corresponding to the formula $(FeNi)_3C$; *schreibersite,* a phosphide of the same metals (with a little cobalt) having the formula $(FeNi)_3P$ or perhaps Fe_2NiP; *oldamite* (calcium sulphide); *daubréelite,* a double sulphide of iron and chromium, $FeCr_2S_4$, which is the sulphur analogue of chromite; *moissanite* or carborundum (silicon carbide, Si C); *merrillite,* a rare phosphate corresponding to the formula 3 CaO, Na_2O, P_2O_5; and *maskelynite,* once thought to be a distinct mineral of isometric crystallisation, but generally regarded now as melted-up plagioclase felspar.

The Texture of Meteorites.

In respect of texture, meteorites fall into two main groups. Those of one group resemble products formed by the crystallisation of a liquid magma; those of the other group are comparable rather to volcanic breccias and tuffs. To the magmatic group belong most of the irons and only a few stones, the majority of meteoric stones being brecciated or tuffaceous.

The iron meteorites (*siderites*) show three varieties of texture, characterised respectively by (a) the arrangement of plates of kamacite parallel to the faces of a cube (hexahedral irons, or Hexahedrites; (b) the arrangement of plates of kamacite and taenite parallel to the faces of an octahedron (octahedral irons or Octahedrites); (c) an apparent absence of any regular structure (Ataxites). Accessory minerals such as schreibersite, cohenite and pyrrhotite are generally present; they form irregular nodules in the nickel-iron, and it is clear that they were the first substances to crystallise; they were followed by kamacite, taenite, and plessite, in that order.

In the *syssiderites* there is a continuous, sponge-like matrix of nickel-iron enclosing isolated grains of olivine or pyroxene. These are sometimes well-formed crystals, but more frequently rounded or broken grains; and the iron itself may show a brecciated structure. The " pallasites " of Krasnojarsk and Imilac, specimens of which are to be seen in most meteorite collections, are beautiful examples of this type.

The structure of the *aerolites* or meteoric stones naturally interests us more than that of the irons. In those stones which hold

little nickel-iron, and which in that respect resemble terrestial rocks most closely, the texture is often ophitic and quite comparable to that of a gabbro or basalt. The Juvinas stone, for example, consists of augite and anorthite in ophitic intergrowth, with a little chromite, magnetite and pyrrhotite; it exhibits drusy cavities, which are lined with well-formed crystals. The Jonzac stone is as coarse-grained as many gabbros, some of the anorthite crystals exceeding a centimetre in diameter. Such stones are generally given the name "eucrite," which was originally applied to an anorthite-gabbro. There are also granular stones such as Chassigny, which are composed of uniform grains of olivine or pyroxene, often held together very loosely. Of the Bishopville stone, M. E. Wadsworth wrote that "the structure is essentially granitic, and it appears to belong to the gabbro (norite) variety of the basalts."

It must be admitted that stones which resemble eruptive rocks as closely as these do are very rare. Among the brecciated stones, however, there are many, such as Petersburg and the "howardites," which are made up of fragments of ophitic stones. G. T. Prior says of the brecciated Simondium meteorite that it "resembles in many parts a terrestial basalt perhaps more closely than any other meteorite." In thin sections under the microscope, this meteorite shows particles of metallic iron, in grains generally less than a millimetre in diameter, large rounded olivine crystals, and smaller irregular grains of enstatite, lath-shaped felspars (labradorite to anorthite), and grains of magnetite. As for the Stannern stone, if it had not actually been observed to fall, it is difficult to see how it could be distinguished from a terrestrial basalt-tuff.

The great majority of stony meteorites have a characteristic texture to which no exact analogue can be found among eruptive rocks. They are made up largely of little rounded bodies (chondrules) of various kinds, embedded in a fragmental base. A common type of chondrule is a little spheroid composed of one or more well-formed, rounded, or skeleton crystals of olivine, intergrown with glass. In another type there is a fibrous structure, due to eccentrically arranged needles of enstatite, which seem to show, by this arrangement, that crystallisation started from the outside of the chondrule. Other chondrules contain both olivine and enstatite, together with glass; others contain nickel-iron; some hold plagioclase; and some are just little drops of glass. Chondrules are typically spheroidal in form, but they are fre-

quently flattened or indented, and entire chondrules and broken ones are often found together. Occasionally a large chondrule is seen to enclose a smaller one. Chondrules have been supposed to have originated through the rapid cooling of liquid silicates, thrown up by explosive action into a hot (solar? stellar?) atmosphere. This view implies a mode of formation comparable with that of a tuff.

L. L. Fermor has suggested that chondrules represent former garnet crystals which have been melted and recrystallised, but the variable composition of chondrules, and the scarcity of alumina as compared to magnesia in chondritic meteorites, seem to put this suggestion out of court. In respect of their mineralogical composition, internal structure, and especially in respect of the presence of glass, chondrules are altogether different from the spherulites of terrestial lavas.

Entire meteoric stones are surrounded by a thin crust of glass, generally of a very dark colour owing to the presence of minute grains of magnetite. The crust is believed to be formed during the passage of the stone through the atmosphere. Thin branching veins of a similar dark glass often traverse the interior of a stone; they resemble the veins of " pseudotachylyte " which are developed in certain ancient rocks in South Africa, India and Scotland. Pseudotachylyte is an incompletely vitrified silicate glass, generated within fissures in granite, gneiss and other hard rocks which have been subjected to violent mechanical shock in consequence of faulting or of sudden injection of magma (S. J. S.). The resemblance between pseudotachylyte veins and the dark veins in meteoric stones may be held to support the view that meteorites have been produced by the sudden disintegration of some larger celestial body.

Classification and Description of Meteorites.

Until quite recently, meteorites were classified primarily on the basis of texture, with little regard to composition except as concerns the proportion of nickel-iron. A quantitative chemical classification of meteorites, on the lines of the norm classification of eruptive rocks, has been introduced by O. C. Farrington. The classification of G. T. Prior is a genetic one, based on the hypothesis that meteorites have separated from a single magma which has passed through successive stages of progressive oxidation. Since the metallic nickel cannot become oxidised until all the iron is in the state of oxide, as has already been shown, it

follows that the ratio of Fe : Ni in the metallic portion is related to the stage of oxidation of the magma.

Prior recognises the usual four classes of irons, stony-irons, chondritic stones and achondritic stones, and within each class he set up four groups with the following critical characters :—

Group 1—Nickel-iron :—ratio Fe : Ni greater than 13.
Magnesian silicate :—enstatite with scarcely any iron.
Felspar :—oligoclase.

Group 2—Nickel-iron :—ratio Fe : Ni less than 13, greater than 8.
Magnesian silicates :—bronzite and olivine, containing more than four times as much magnesia as iron oxide.
Felspar :—oligoclase.

Group 3—Nickel-iron :—ratio Fe : Ni less than 8, greater than 2.
Magnesian silicates :—hypersthene, clino-pyroxene and olivine, having less than four times, but more than twice, as much magnesia as iron oxide.
Felspar :—oligoclase.

Group 4—Magnesian silicates :—clino-pyroxene and olivine, having MgO : FeO less than 2.
Felspar :—anorthite.

In order to illustrate the variations in the composition of meteorites, for the purpose of comparing them with terrestrial rocks, we shall give the mineralogical composition (mode) of a number of examples, arranging them simply in the *order of increasing content of nickel-iron.* In view of the scarcity of quantitative descriptions of eruptive rocks, it is interesting to find that in most accounts of meteorites the mineralogical composition is stated quantitatively and very accurately.

It is among the stones containing *less than* 10 *per cent. of non-silicates* that the closest resemblance to eruptive rocks is observed. The Juvinas stone, to which we have already referred, has according to C. Rammelsberg the following composition, which is just that of an anorthite-gabbro :—

pyroxene	62.6	chromite	1.3
anorthite	34.5	magnetite	1.2
apatite	0.6	pyrrhotite	0.2

The Petersburg stone is a brecciated eucrite, very similar to Juvinas in composition; Rammelsberg gives pyroxene 68.6, anorthite 30, pyrrhotite 0.6, in this case. In the Sherghotty eucrite, G. Tschermak found pyroxene 73.4, plagioclase (maskelynite) 22.5, magnetite 4.5. The Shalka stone is practically a pyroxenite, consisting almost entirely of a variety of hypersthene rich in ferrous oxide.

None of the above stones contains any olivine. In the Hendersonville chondritic stone olivine is an important constituent. The following mode is given by G. P. Merrill :—

pyroxenes	51.62	nickel-iron	2.59
olivine	40.48	troilite	4.43
chromite	.80	schreibersite	.08

The Goalpara stone (achondrite), as described by G. Tschermak, contains 62 per cent. of olivine, 30 of pyroxene (clino-bronzite according to Prior), and 8½ per cent. of nickel-iron. A still higher content of olivine appears in the Ornans stone, which F. Pisani has analysed with the following result :—

olivine	75.10	nickel-iron	1.85
pyroxene	15.26	chromite	0.40
troilite	6.81		

Finally, in Chassigny, we have an example of a stone that is almost entirely composed of olivine (rich in ferrous oxide) with just a little chromite and pyroxene.

Coming next to meteorites that hold *between* 10 *and* 30 *per cent. of non-silicates,* we find an olivine-free example in the Khairpur stone, which belongs to Prior's group of enstatite chondrites. The mode given by Prior is

enstatite	60.31	chromite	.39
oligoclase	8.25	daubréelite	.29
nickel-iron	18.29	oldhamite	.34
troilite	7.03	graphite	.41
		rust, etc.	4.39

Stones that contain olivine are much commoner than the above type. Prior has shown that most chondritic stones approximate to one chemical and mineralogical type, of which the average composition is as follows :—

olivine	44	nickel-iron	9
bronzite	30	troilite	6
felspar	10	chromite, etc.	1

How closely some of these stones, found in widely separated regions, resemble one another, and how nearly they approach the above average, may be shown by quoting Prior's own analyses of the Launton stone, which fell in England in 1830, the Amana or Homestead stone (Iowa, 1875), and the Baroti stone (India, 1910).

	Launton	*Amana*	*Baroti*
felspar	10.82	9.76	10.25
olivine	41.91	40.15	42.12
bronzite	29.50	30.75	30.38
nickel-iron	8.48	10.99	8.91
troilite	5.98	6.25	6.79
apatite	.36	.22	.56
chromite	.45	.44	.27
magnetite, ilmenite	.33	—	.94

Among the meteorites containing *between* 30 *and* 60 *per cent of non-silicates,* Daniel's Kuil is olivine-free and Saint-Sauveur holds very little olivine. The first of these modes is by G. T. Prior, the second by A. Lacroix.

	Daniel's Kuil	*St. Sauveur*
felspar	8.47	13.38
enstatite	55.76	41.25
olivine	—	1.40
nickel-iron	25.45	27.49
troilite	7.96	14.26
oldhamite	.86	1.15
daubréelite	.40	.22
chromite	.34	—
apatite	—	.34
graphite	.32	.10

In Hainholtz and Vaca Muerta, which hold almost equal parts of silicates and non-silicates and fall in the group of *mesosiderites,* olivine is again very scantily represented. Both modes are by G. T. Prior.

	Hainholtz	*Vaca Muerta*
anorthite	14.5	17
pyroxene	27	32
olivine	1.5	1.5
nickel-iron	46.5	41.5
troilite	4	2
schreibersite, etc.	2	3
chromite	.5	1
rust	4	2

The Mount Vernon meteorite is a pallasite unusually rich in olivine. W. Tassin gives its composition as follows :—

olivine	63.15	chromite	1.00
nickel-iron	33.12	troilite	.69
schreibersite	1.95	carbon	.09

Other pallasites, such as Krasnojarsk, hold more nickel-iron, and generally *from 60 to 90 per cent. of non-silicates.* The siderolite recently described by A. Lacroix, from the Adrar desert, also falls within this range of composition, but is nearly free from olivine. The mode is

felspar	1.7	nickel-iron	71.2
hypersthene	17.3	troilite	8.3
olivine	0.9	schreibersite	0.5

Coming now to meteorites with *more than 90 per cent. of non-silicates,* we may quote the Tucson iron, which still contains a little olivine and is therefore intermediate between the pure irons and the pallasites. J. L. Smith has given the following mode :—

nickel-iron	93.81	schreibersite	0.94
olivine	5.06	chromite	0.41

We conclude with a few examples of siderites containing no silicates at all. The Wichita octahedrite, according to E. Cohen's analysis, contains 85 per cent. of kamacite, 2.6 of taenite, 6.3 of schreibersite, and 6 per cent. of cohenite. For the Zacatecas iron, which is also an octahedrite, Cohen gives the following data :—

nickel-iron	95.04	nickel phosphide	1.08
schreibersite	3.06	carbon	0.03
troilite	0.26	chromite	0.07
daubréelite	0.02	residue (containing copper)	0.44

The Mart iron, with a still greater proportion of metal, also belongs to the octahedrites. Its composition has been determined by G. P. Merrill and H. N. Stokes to be

nickel-iron	98.31	troilite	0.05
schreibersite	1.06	chromite	trace

For the Coahuila iron, a hexahedrite, E. Cohen gives the following mode :—

nickel-iron	98.3	carbon	.011
schreibersite (rhabdite)	1.6	chromite, etc.	.003
daubréelite	.027		

REFERENCES.

Cohen, E.—Meteoritenkunde, 1905.
Daubrée, A.—Etudes synthétiques de géologie expérimentale, Part II., Paris, 1879.
Farrington, O. C.—(1) Meteorites. Chicago, 1915.
(2) Catalogue of the Meteorites of N. America; Mem. Nat. Acad. Sci., vol. 13; Washington, 1915.
Fletcher, L.—Introduction to the Study of Meteorites. British Museum.
Flight, W.—A Chapter in the History of Meteorites, London, 1887.
Lacroix, A.—(St. Sauveur) Comptes Rendus, 1923, *561*.
do. —(Adrar) Comptes Rendus, 1924, *309*.
Merrill, G. P.—(Composition) Amer. Jour. Sci., 1909, *471*.
Prior, G. T.—(Amana) Mineralog. Mag., 1918, *173*.
do. —(Baroti) Mineralog. Mag., 1913, *22*.
do. —(Chondrites) Mineralog. Mag., 1913, *33*.
do. —(Classification) Mineralog. Mag , 1916, *26;* 1920, *51*.
do. —(Daniels Kuil) Mineralog. Mag., 1916, *13*.
do. —(Hainholtz) Mineralog. Mag., 1918, *158*.
do. —(Khairpur) Mineralog. Mag., 1916, *17*.
do. —(Launton) Mineralog. Mag., 1916, *2*.
do. —(Simondium) Mineralog. Mag., 1910, *312;* 1918, *161*.
do. —(Vaca Muerta) Mineralog. Mag., 1918, *152*.
Shand, S. J.—(Pseudotachylyte) Quart. Jour. Geol. Soc., 1917, *198*.
Wahl, W. A.—Zeitschrift für Anorg. Chem., 1910, *67*.
Wülfing, E. A.—Die Meteoriten in Sammlungen, Tubingen, 1897.
(For all other references and descriptions, see Farrington (2), Flight, or Wülfing.)

CHAPTER XVI.

ERUPTIVE ORE DEPOSITS.

Just as there are three genetically distinct groups of rocks, the eruptive, the sedimentary, and the metamorphic, so there are three prime groups of ore deposits, as follows :—

Eruptive ore deposits, in which the concentration of the useful mineral has been effected by eruptive magma or magmatic emanations;

Sedimentary ore deposits, in which the concentration has been effected by surface agents such as air, water and organisms; and

Deposits concentrated by ground-water after the formation of the containing rock, whether eruptive or sedimentary.

It is only with the eruptive deposits that we shall be concerned here, and the position that will be taken in regard to them has already been indicated in Chapter I. It is, in brief, that the eruptive rocks and the eruptive ore-deposits form a continuous series in which the temperature of formation falls steadily from that end to this, while the water content (or more generally the content of fugitive substances) of the magma-solution rises in the same direction. The formation temperature of the various members of the series ranges from over 700° down to less than 375° (the critical temperature of pure water).

Among the eruptive ore-deposits, we may recognise the following geologically distinct types :—

(1) *Primary disseminations.* The ore (or useful mineral) is scattered through the whole of the eruptive rock.

(2) *Primary segregations.* The ore is concentrated in certain parts of the rock mass.

(3) *Contact deposits.* The ore is concentrated in the zone of contact between the eruptive and the country rocks, partly replacing the eruptive rock itself (*internal* or *endomorphic contact deposit*) but mainly impregnating and replacing the country rock (*external or exomorphic contact deposit*).

(4) *Self-replacements* along pipes and fissures.
(5) *Pegmatite* and *aplite* veins within the eruptive or out in the country rock.
(6) *Quartz veins* within the eruptive or out in the country rock.

Type (1). Primary Disseminations.

Very many useful minerals are disseminated in eruptive rocks; for example felspar itself, and leucite, as well as magnetite, ilmenite, iron and copper pyrites, tinstone, chromite, zircon, monazite, and sometimes gold and native copper; but it is only in the case of a few minerals of great value that the mining, crushing and treatment of a whole rock mass, for the sake of traces of mineral disseminated through it, becomes a practical proposition. For illustrations, we are practically confined to diamond and the platinum metals.

Diamond. Wherever diamonds have been found in the original matrix, that matrix is a rock rich in olivine or its alteration products. The "blue ground" or kimberlite of the diamond fields of South and Central Africa has already been described; it is a serpentinised peridotite containing, in addition to olivine, magnesian pyroxenes, magnesia mica, magnesian garnet, and small quantities of many other minerals. The diamonds of Brazil have in recent years been traced back to their source in a rock of the same kind, and small bodies of kimberlite yield diamonds in Arkansas. In California a few stones have been found in the neighbourhood of serpentine from which they were probably derived by weathering; and at Bald Knob, in Tasmania, diamonds have been found about an intrusion of peridotite. To this rule of association with olivine there is only one rather doubtful exception, which will be noticed below.

All the typical occurrences of kimberlite have the form of nearly vertical pipes and dykes, which have been channels of violent volcanic activity. Much of the South African kimberlite has more of the character of a volcanic breccia than of a normal eruptive rock, and it is full of foreign rock fragments. Some of these fragments have clearly been derived from the stratified formations that form the present walls of the pipes, or that formerly extended over the surface of the country; but others are of eruptive and metamorphic origin, and they must have been carried up from deeper levels in the crust. Among enclosed fragments of the latter type, the most interesting are boulders of

eclogite and of various peridotites containing ortho- and clino-pyroxenes. The abundance and variety of these enclosures have led A. L. du Toit to the conclusion that "kimberlite has been produced by the shattering of various holocrystalline basic and ultra-basic rocks and the incorporation of this material by a magma of ultra-basic character." Other students of kimberlite have regarded these peridotite and eclogite boulders rather as segregations from the kimberlite magma itself; a view which derives some probability from the observation made by J. Morozewicz, that when artificial melts containing magnesian silicates are allowed to crystallise, the first-formed crystals tend to form concretionary groups. Du Toit maintains that the granulites and eclogites, in particular, exhibit no affinity to kimberlite, and that there is no justification for regarding them as segregations from the same magma that gave rise to kimberlite.

The point bears upon the genesis of the diamond, because small diamonds have been discovered in eclogite from the Newlands Mine by T. G. Bonney, and on this rather slight foundation the theory has been put forward that all the diamonds in the South African kimberlite have been derived from disrupted eclogite. But the number of stones that have been found in eclogite boulders is negligibly small; two specimens were described by Bonney, and two more have been brought to light since then; while on the other hand G. F. Williams crushed twenty tons of boulders from the Kimberley Mine without finding a single diamond. Du Toit points out that this test cannot be considered conclusive, since the boulders in Kimberley Mine are mostly of peridotite, and eclogite is very rare among them; yet this very point tells strongly against the theory that the diamonds in that mine were derived from eclogite. It is not reasonable to suppose that the eclogite boulders, which are particularly hard and tough, were completely disintegrated while the peridotite boulders survived.

Taking all these points into consideration, it seems unnecessary to look any further than the kimberlite itself for the actual matrix of the diamond. If the eclogite boulders represent early segregations from the kimberlite magma, the occurrence of a few diamonds in them is a thing to be expected, and it does not by any means invalidate the conclusion that the bulk of the stones are primary constituents of kimberlite. The ratio of diamonds to rock is very small; rich blue ground gives roughly one carat of diamonds per ton, or one part by weight in five

millions, and the average over the whole of a big mine is much less. In the Premier Mine, Transvaal, the yield is said to be only one part in seventeen and a half millions.

Metals of the platinum family. Platinum, which is generally associated with variable quantities of palladium, iridium, osmium, ruthenium and rhodium, is a constituent of many melanocratic rocks, especially perknites and peridotites. In the past, commercial supplies of " platinoids " were obtained exclusively from placer deposits, where a natural separation of the heavier from the lighter grains of rock detritus has been effected by running water; but recent discoveries in the Transvaal have shown that it is practicable to extract the metal directly from its eruptive matrix.

The platinum of the Ural Mountain region, which formerly gave quite 95 per cent. of the world's production, is a primary constituent of the dunites and peridotites to which we referred on page 220. Assays of these rocks have returned as much as 22 grams (13 pennyweights) of platinum per ton of rock (R. Helmhacker), but the richness of the alluvial deposits in the beds of streams draining the country made it unnecessary to attack the problem of extracting the finely divided metal from the peridotite.

The platinum deposits in the Yale district of British Columbia are comparable in every geological circumstance with those of the Ural Mountains. The parent rock is a pale green dunite, consisting almost entirely of olivine and chromite (E. Poitevin). The alluvial platinum of Minas Geraes, Brazil; of the Rio Pinto, Colombia; and of Borneo and New Zealand is also found in the beds of streams which drain areas of peridotite and serpentine. In the Heazlewood district of Tasmania, osmiridium has been found in serpentine derived from various types of peridotite, but not, it is said, in serpentine formed from pyroxenite or gabbro (A. M. Reid).

Platinum was detected many years ago in the hypersthenites and chromite seams of the Bushveld norite, in the Transvaal, but not in payable quantity. Since 1924, it has been rediscovered almost all round the margin of the Bushveld complex. The most extensive occurrence is in a persistent horizon of norite containing scattered grains of iron- and copper-sulphides; this horizon has been traced for a distance of nearly four hundred miles along the outcrop of the norite sheet. The rock consists of labradorite

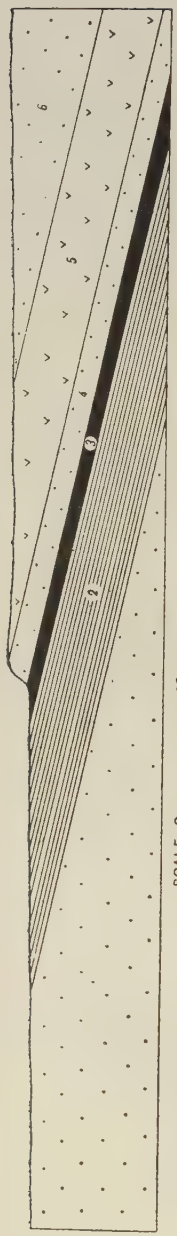

FIG. 38. Section showing the differentiation of the Bushveld norite in the eastern Transvaal, and the position of the platinum-bearing horizon. (P. A. Wagner.)

1. Medium-grained spotted Norite.
2. Felspathic pyroxenite, merging upward into
3. *Platinum-bearing Norite*
4. Light coloured spotted Norite.
5. Mottled Anorthosite.
6. Coarse-grained spotted Norite.

and two kinds of pyroxene (bronzite and diallage), with a little chromite, magnetite, apatite and hornblende. The pyroxenes generally predominate over the felspar, and the specific gravity of the rock ranges from 3.1 to 3.26. The platinum content of this rock depends on the appearance in it of little interstitial grains of sulphides of iron, nickel and copper (the minerals pyrrhotite, pentlandite and copper pyrites), in which the platinum is somehow locked up. P. A. Wagner states that a definite relation has been established between the platinum content of the rock and the percentage of sulphides present. The proof that these sulphides are indigenous to the rock, and were not introduced by solutions from outside, is afforded by the textural relations of the various minerals in the rock, and by the observation that lenses of the sulphidic norite are sometimes completely enclosed in anorthosite which contains no sulphides. As Wagner says, " it is inconceivable that vagrant mineralising solutions could have picked out such lenses and impregnated them with sulphides without leaving any trace of their passage in the surrounding rocks." The average platinum content of this rock is two or three pennyweights, rising locally to five or six pennyweights, per short ton. (*Fig.* 38.)

The Transvaal also furnishes another type of platinum dissemination, this time in a dunite, or olivine rock. This rock differs from the dunites of the Ural Mountains and other platinum mining regions, in being composed of a variety of olivine unusually rich in iron—it holds approximately equal molecular proportions of the forsterite and fayalite molecules—and in consequence the colour of the rock is brown instead of green and its specific gravity reaches the unusually high value of 3.7 to 3.9. This rock forms pipe-like bodies, veins and irregular segregations in pyroxenite in the lower zones of the Bushveld Complex; the occurrences are numerous, but mostly of small dimensions, and only a few of them are platiniferous. The most remarkable occurrence is a pipe-like body on the farm Onverwacht, in the Lydenburg district, only sixty feet in diameter, which has given assay values of nearly 140 pennyweights to the ton (.0234 per

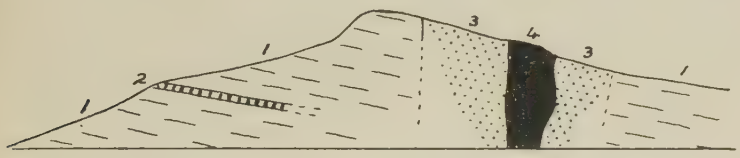

FIG. 39. A pipe of platinum-bearing dunite cutting the pyroxenite zone of the Bushveld norite; Lydenburg, Transvaal. (After P. A. Wagner.)

1, pyroxenite; 2, chromite seam; 3, magnesia-rich dunite, occupying a pipe of uncertain shape; 4, iron-rich platiniferous dunite, forming a pipe within No. 3. Scale, one inch = 300 feet.

cent.) though the average is much less. The mineralogical composition of this rock was given on page 264; the platinum is present in the form of minute cubes and irregular grains enclosed in olivine or magnetite (P. A. Wagner). (*Fig.* 39.)

TYPE (2). PRIMARY SEGREGATIONS.

It is not invariably easy in practice to distinguish deposits of this class from contact deposits, for there are some ore bodies that share the characters of both classes, being partly due to original segregation of ore within the magma, and partly to subsequent redistribution of the ore, and its introduction into the country rock, by escaping magmatic solutions. In the case of one of the largest deposits to which the segregation theory has been applied, namely the copper-nickel ore of Sudbury, Ontario, it seems likely that more than one cause has been operative, hence that deposit can only be referred to the present class with certain

qualifications. Nevertheless, the proper way to study a complex phenomenon is to split it up into its constituent elements; and among the elements that contribute to the formation of ore-deposits within eruptive rocks, direct segregation by the magma itself must be taken into account. It will be seen in the following pages that there are many cases of ore-segregation which completely fulfil the requirements of the present class.

The metalliferous minerals that most commonly form segregations within eruptive rocks are the following: magnetite, ilmenite, chromite, spinel; pyrite, pyrrhotite, chalcopyrite, niccolite, mispickel. The first four are oxides, the remainder sulphides and sulpharsenides of iron, nickel and copper. Along with these there may be small but important quantities of other minerals such as pentlandite (nickel sulphide), molybdenite, smaltite and cobaltite, sperrylite (platinum arsenide), and the sulphides, arsenides and antimonides of silver.

The "oxidic" segregations seldom contain any admixture of sulphides, and the "sulphidic" segregations are often nearly free from oxides. Exceptionally, oxides and sulphides occur side by side; as at Malaga, Spain, where chromite and niccolite are associated (F. Gillman), and at Hatfjelddal, Norway, where a serpentine contains sulphides of copper and also kidneys of chromite. J. H. L. Vogt has pointed out a very important difference between the two types of segregation, namely, that oxidic segregations are nearly all found *within* the eruptive, often in the centre, whereas sulphidic segregations are mostly confined to the margin, and generally lie along or close to the contact between eruptive and country rock. To this rule there are exceptions, for the iron ore in the Carrock Fell gabbro is concentrated towards the margins of the rock, while in Tuscany and in Namaqualand sulphide ores occur in lenses and pockets through the whole mass of the containing rocks.

A sharper distinction between oxidic and sulphidic segregations is found in the period of crystallisation of the ore-minerals. The oxides are always found to have crystallised before the associated silicates, and the sulphides, when they are abundant, after the silicates. Connected with the early crystallisation of the oxides is the fact that concentration of oxides is always accompanied by concentration of other minerals of early crystallisation such as olivine, pyroxene, apatite, and zircon. For all the above reasons it is advisable to consider the oxidic and sulphidic segregations separately.

A. Oxidic segregations. As a simple illustration, involving no complications whatever, we may consider the concentration of the titaniferous iron ore at Carrock Fell, as described by A. Harker. The rock is a quartz-gabbro with the usual small content of iron ore. Towards the margins of the exposure the gabbro becomes gradually richer in iron ore and at the same time loses its quartz. At the actual border the rock holds as much as 27 per cent. of titaniferous magnetite. The density of the rock varies from 2.68 in the interior to 3.27 at the margin. Harker states that "there is throughout a gradual transition from one variety to another, and for the most part the constituent minerals are the same, but associated in different proportions."

At Taberg, Sweden, an olivine gabbro rather poor in magnetite contains, and passes quite gradually into, a core of basic rock consisting of titaniferous magnetite and olivine, with some biotite and labradorite, and eventually into a pure magnetite-olivine rock. In an otherwise similar case at Kragerö, Norway, the ore body consists of ilmenite and enstatite instead of magnetite and olivine.

In the district of Ekersund, in southern Norway, oxidic ore-bodies are associated with an eruptive complex which is in the main an anorthosite (labradorite rock) but which passes on the one hand into an enstatite-granite and on the other hand into an ordinary norite composed of plagioclase, hypersthene and biotite. The anorthosite is cut by dykes of norite and of a norite-pegmatite rich in ilmenite. The main ore-bodies occur within the anorthosite and consist of bands and dykes of nearly pure ilmenite with only traces of labradorite and hypersthene. There is generally a sharp boundary between ore and rock, but according to J. H. L. Vogt every intermediate mixture between anorthosite and pure ilmenite is represented somewhere in the field. (*Fig.* 40.)

The iron-ore deposits of the Adirondacks, in Essex County, New York, are developed under circumstances almost identical with the above. The largest bodies occur in anorthosite, and smaller bodies in gabbro and norite. The ore in the gabbro is microcrystalline and mixed with dark silicates; that in the anorthosite is coarsely crystalline and contains some felspar. The transition from ore to rock is rapid but not sharp, and J. F. Kemp states that the ore masses "vary from rich titaniferous iron oxide through leaner and leaner examples until normal gabbro is reached."

At Pitkäranta, Sweden, a gabbro contains dark streaks of titaniferous magnetite accompanied by diallage, hornblende, hypersthene and olivine. Some of these streaks are poor in ore, others contain as much as 50 to 60 per cent. of magnetite together with green spinel and a small proportion of sulphides. There is a similar occurrence at Routivaara, Finland, where an altered gabbro has a core of magnetite-spinel rock. Besides the ores, some olivine and hypersthene are present. The order of crystallisation of these minerals was as follows: spinel first, followed by spinel and magnetite, then magnetite and olivine. This interesting occurrence, with its singularly high content of spinel (pleonaste or hercynite) has been described by W. Pettersen and H. Sjögren.

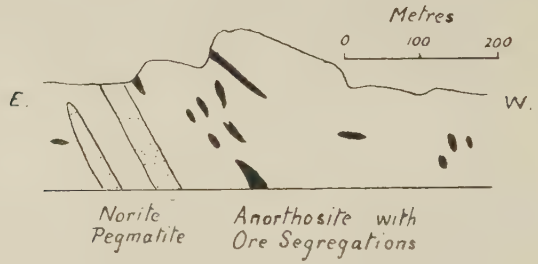

FIG. 40. Ore-bodies in anorthosite at Blaafjeld, Norway. (After J. H. L. Vogt.)

In all the above instances the ore is genetically connected with bodies of gabbro, norite or anorthosite; in some rarer, but economically important, cases the ore-body has been developed in connection with granitic or syenitic rocks. In the mining district of Nijni-Tagilsk in the Ural Mountains, the magnetite deposits which have been worked for two hundred years are associated with intrusions of augite syenite and orthoclase-porphyry. The latter rock contains grains of magnetite which are in places aggregated together to form small rounded masses; these become larger and larger, and eventually pass into big bodies of ore of great purity. At Gorablagodat, in the same region, the ore forms streaks and bands within the porphyry, the transition between rock and ore being a gradual one. A. Högbom and Th. Tchernichev have regarded these deposits as magmatic segregations, but according to R. Beck they are due rather to a combination of magmatic segregation and contact metamorphism.

N. Yakowlew also regards the Nijni-Tagilsk ore as a contact deposit. This is another illustration of the difficulty of holding these two classes apart.

The great magnetite deposits of Kirunavaara (Kiruna), Sweden, have been studied by A. G. Högbom, P. Geijer, H. Lundbohm, and more recently by R. A. Daly. The main ore-body lies between two mighty intrusions, one of quartz-porphyry, the other of syenite-porphyry and syenite. The ore is mainly magnetite, with variable amounts of silicates and apatite. The main body is 3,000 metres long and has an average thickness of 78 metres; it is said to be the largest body of high-grade ore being worked in any country. The ore is considered to be younger than the syenite-porphyry and nearly contemporaneous with the quartz-porphyry, but there is still some difference of opinion regarding the genesis of the deposit. P. Geijer strongly supports the view that the ore is of magmatic origin, for the following reasons:—

(1) The minerals occurring in the ores are all such as are primary minerals of the eruptive rocks;

(2) Structural phenomena show that the ore mass has crystallised in the same way as a normal eruptive rock. These phenomena are flow-structure, skeletal form of magnetite crystals, ophitic texture of augite, etc.;

(3) The geological mode of occurrence of the ore is consistent with this explanation;

(4) In the porphyries there are dykes and lenses of evident magmatic origin, which are similar in composition and structure to one or another of the ore varieties.

R. A. Daly also upholds this view. He considers the small ore-bodies in the quartz-porphyry to be true segregations from the magma, and believes that the main ore body was formed by the sinking of millions of these small masses to the floor of the porphyry laccolite. The Kiruna ore is an extremely pure magnetite, carrying less than 1 per cent. of TiO_2; Vogt remarks that such pure magnetite deposits are only found in connection with acid rocks; the ore associated with gabbro, norite or anorthosite is always titaniferous, holding at least 5 per cent. of TiO_2.

Deposits of chromite and chrome-spinel are chiefly found in olivine rocks (peridotite and serpentine), within which the ore forms ill-defined streaks and enrichments. J. H. L. Vogt recognises about a hundred such occurrences in Norway alone, and notes that the chromite was in every case the first mineral to crystallise. On the island of Hestmandö, the ore occurs in a

perfectly fresh olivine-enstatite rock (harzburgite) of which there are some twelve small masses, none exceeding half a kilometre in diameter. Chromite and picotite are present in every specimen of the rock, and are concentrated here and there in streaks, clumps, and trains of clumps. There is a perfect gradation from rock to ore-body, and in every case the enrichment is entirely of minerals present in the harzburgite, no new minerals appearing in the ore-bodies. No trace of ore is found outside the eruptives. A rough proportionality is observed between the mass of each eruptive and that of the corresponding ore-body.

Extensive deposits of chromite are worked in Asia Minor, near Smyrna, where there are over a hundred separate occurrences of chromite in serpentine. At Kraubath, in Styria, the ore-bringer is a fresh dunite or olivine rock. At Dun Mountain in New Zealand the matrix is the same but it has largely been changed to serpentine. A very important occurrence is that of Selukwe, Rhodesia; the ore is found both in ancient talc-schists, which are believed to be altered olivine rocks, and in the serpentine of the Great Dyke. In the former case the ore forms irregular lenses and tabular masses up to 500 feet long and ten or twenty feet thick. The more compact bodies have sharp boundaries, the less compact grade off into the country rock (A. E. V. Zealley). In the serpentine of the Great Dyke the ore occurs in parallel sheets and streaks, generally less than a foot thick.

The chromite deposits in the Bushveld norite of the Transvaal are peculiar in that they are associated with enstatite or hypersthene more frequently than with olivine. The parent rock is a norite containing plagioclase and hypersthene; where segregations of chromite occur the heavy hypersthene has been concentrated too, and according to A. L. Hall and W. A. Humphrey the dark hypersthene rock can be used as an indicator in tracing the chromite bodies. In this case again the chromite was the first mineral to crystallise, and there is no sharp line of division between ore and country rock. A good account of these chromite deposits is given by P. A. Wagner, who considers them to have been formed by simple gravitative accumulation.

An instance of wolfram occurring in magmatic segregations has been described by F. L. Hess, in the granite of the Whetstone Mountains, Arizona. The wolfram appears in dark streaks in certain parts of the rock, looking quite like the streaks of hornblende and mica that one sees in many granites. The occurrence

is of little economic importance, but it possesses the interest that attaches to a unique phenomenon.

Enough has been said to show that there is an important group of oxidic ore-deposits formed by direct segregation from eruptive magma. The primary origin of the ore is shown by (1) the gradual transition that can be observed in most cases from rock poor in ore to rock greatly enriched with ore; (2) the concurrent increase of ore with that of the heavy silicates of the rock; (3) an approximate correspondence between the bulk of the ore-bringer and that of the ore-body; (4) the regular sequence of crystallisation that is observed between oxides and silicates, the oxides having crystallised first; (5) the occurrence of similar ore-bodies in similar eruptive rocks in many parts of the world; (6) the general absence from these deposits of any minerals other than those that are original constituents of the eruptive rocks in which the deposits are found.

Although the facts are indisputable, the cause of the segregation remains to be sought. In a few cases (*e.g.*, Kiruna) the ore-body lies at the lower margin of the eruptive, and it is possible to account for the deposit by a simple process of settling of the early-formed crystals. There has been a reluctance on the part of geologists to admit the possibility of gravitational settling, because of the prevailing idea that a silicate magma must necessarily possess a high viscosity. Yet the settling of early formed crystals has been observed in nature—C. L. King noticed the sinking of augite and felspar crystals in liquid lava at Kilauea—and it has been demonstrated in the furnace and the crucible. J. Morozewicz records the sinking of magnetite crystals in a melt of ordinary glass, to such an extent that the melt had after cooling a density of 2.634 in its upper layers and 2.996 below. N. L. Bowen has demonstrated the sinking of olivine and the rising of quartz-grains in a few cubic centimetres of melt in a crucible.

Now the viscosity of a natural magma is certainly lower than that of a melt of the same composition, so there can be no doubt that the same action is possible in nature, especially in the case of minerals so different in density as silicates and ores. To this cause, then, we may reasonably refer some part of the phenomena described above, especially in those cases where the ore forms tabular bodies at the base, or parallel to the base, of the eruptive rock. But the ore often forms lenses, nests, and irregular patches which are distributed without any apparent regularity throughout the eruptive; in such cases another cause must be sought.

Observation in many localities shows a tendency, on the part of olivine-rich magmas especially, to segregate their earliest formed crystals in irregular "concretions." Many olivine-basalts, for example, contain rounded or angular lumps of nearly pure olivine which have often been looked upon as inclusions of foreign rock. In his experiments upon artificial melts of basaltic and andesitic composition, J. Morozewicz found that the early-formed olivine, spinel and corundum tended to form just such aggregates in the heart of the melt. But the recognition of a "tendency" of this kind leaves us as ignorant as before of its cause. A magnetic attraction between the ore-particles has been suggested, but the difficulty about accepting this as a hypothesis is that in the case of iron the temporary magnetism is destroyed when the temperature rises above 300°.

The law known as Soret's Principle has been invoked to explain some of the phenomena of differentiation and segregation. This law states that when a solution is in a state of equilibrium the concentration of the dissolved substance varies inversely as the absolute temperature; thus the cooler parts of a solution are slightly more concentrated than the rest. But it is obvious that the extreme range of concentration (almost 0 to 100 per cent.) which is met in some of the cases described above can not possibly be explained in this way. A. Harker, in discussing the phenomena observed by him at Carrock Fell, lays emphasis on the fact that the minerals that have been concentrated in that case, namely magnetite, ilmenite and apatite, are those of early crystallisation. He considers that the growth of these minerals began first at the margin of the gabbro intrusion, and that diffusion was then set up in the magma, whereby fresh supplies of the molecules of these minerals were carried continuously towards the margin until the increasing viscosity of the magma put a stop to further diffusion. One can imagine that in this way a marginal body of nearly pure ore might be formed if the cooling of the magma was sufficiently slow. Yet this leaves unexplained the more numerous cases of segregation within the heart of the eruptive.

In certain cases the ore-body has been regarded as a separate intrusion, younger than the eruptive rock, or else as an immiscible liquid phase of the magma with which it is associated. The former view has been advanced by A. L. du Toit to account for an occurrence of titanomagnetite in sheet form in gabbro in the Tugela Valley, Natal; while the latter explanation is favoured by

J. F. Kemp in the case of the Adirondack ores. Objection to these views arises out of the high melting points of the oxidic ores, the frequent evidence of gradual transition from pure rock to nearly pure ore, the concurrent increase of ores with that of the other minerals of early crystallisation, and the frequently observed correlation between the mass of the ore-bringer and that of the ore-body. There is great need of further observation and experiment to solve the problem of the formation of these magmatic segregations.

B. Sulphidic Segregations. Segregations of pyrrhotite and sulphides of copper, nickel and cobalt, are characteristically developed in connection with gabbro and norite intrusions. In the foregoing accounts of oxidic segregations it will be noticed that pyrrhotite and chalcopyrite are sometimes reported to be present in small quantity among the oxidic ores. In the same way the sulphidic ore-bodies may contain certain oxides, especially magnetite, but it seldom happens that one and the same eruptive rock holds both sulphidic and oxidic segregations in anything like equal development. Yet the rock that holds oxidic ores in one locality may be identical in every lithological character with the rock that in another locality yields only sulphides. In a very general way, however, the following rules seem to hold good:—

Pure magnetite occurs only in rocks of high acidity, as granites, syenites, and their porphyries and pegmatites.

Sulphidic ores (pyrrhotite, pentlandite, chalcopyrite, bornite) occur especially in diorites, gabbros and norites, mostly without olivine.

Titaniferous magnetite and ilmenite occur in gabbros, norites and anorthosites, either with or without olivine.

Chromite occurs almost exclusively in rocks rich in olivine or hypersthene.

The sulphidic ore-bodies of Norway have been very fully described by J. H. L. Vogt, who enumerates over forty occurrences of gabbro or norite with segregations of nickeliferous pyrrhotite. The ore-bringer is more commonly norite than gabbro, and does not as a rule contain olivine. At Bamle, Hoias, and Romsaas the rock is a simple norite containing little or no olivine or diallage, but often holding some biotite and hornblende. In the Erteli region there is a variety of types, connected by transitional facies; such as norite without olivine or diallage; diallage norite without olivine; olivine norite without diallage; gabbro without

hypersthene; olivine gabbro with or without hypersthene. All the rocks of this region are poor in biotite. At Tromsö and Espedal olivine is sometimes present, and there is a good deal of hornblende; and at Värdalen both olivine norite and olivine gabbro are represented. In Smaland, Sweden, the ore-bearer is a gabbro which contains hypersthene but no olivine, and sometimes holds both quartz and orthoclase. In several of these areas the main rock-body is cut by granitic pegmatite dykes in which pyrrhotite and chalcopyrite are present along with quartz and alkali-felspar.

In all these cases the pyrrhotite and to a lesser extent the pyrite and chalcopyrite occur as normal accessory minerals of the rock. The ore-bodies are always at or very close to the margin of the intrusion, and in some instances there is a perfect gradation from eruptive rock to ore-body, while in others there is a sharp junction. From the main ore-body, veins of sulphides and sulphide-norite run out both into the country rock and into the eruptive. In all cases, too, the pyrrhotite was the *last* mineral to crystallise whenever it exceeded about one-third of the volume of the rock. Pyrite, when present, crystallised before the silicates.

A very important observation is that there is a rough proportionality between the bulk of the eruptive and that of the ore deposit. Vogt has made approximate calculations to find what the proportions of copper, nickel and cobalt would be if the ores were evenly distributed through the whole mass of the eruptive rocks with which they are connected. His findings are as follows :—

Erteli : Ni 0.03 per cent., Co 0.005 per cent., Cu 0.015 per cent.

Bamle : Ni 0.12 per cent., Co 0.017 per cent., Cu 0.05 per cent.

Beiern : Ni 0.085 per cent., Co 0.008 per cent., Cu 0.02 per cent.

The figures are useful as showing that the magma which gave rise to these large ore deposits held no unusual wealth of heavy metals, for many rocks hold such quantities of these metals as are shown here.

One of the greatest examples of the segregation of sulphides is found at Sudbury, in Ontario. As interpreted and mapped by A. P. Coleman and other officers of the Geological Survey of

Canada, the intrusive rock has the form of a great sill, sagging in the middle; it has a floor of Archæan gneiss and schists, and a roof of Huronian tuffs, slates and schists. The present dimensions of the sill are 36 by 18 miles, and the thickness 10,000 feet. The average rock is a norite containing a little quartz. Towards the upper contact it becomes enriched with quartz and passes into a quartz-syenite or granite; towards the base it is enriched with sulphides, and along or close to the contact there occur large bodies of pyrrhotite and copper pyrites measuring hundreds of feet in length and depth. The nickel, in the form of pentlandite, is locked up in the vastly more abundant pyrrhotite which makes up 70 to 80 per cent. of the ore. These sulphides crystallised *after* the silicates (augite, hypersthene and labradorite) with which which they are associated, the order of crystallisation being (1) pyrrhotite, (2) pentlandite, (3) chalcopyrite. A. P. Coleman showed that there is a relation between the thickness of the sill at any point and the bulk of the ore-body beneath it. This is confirmed by H. M. Roberts and R. D. Longyear, who have succeeded in locating new bodies of ore by means of this observation.

The deposits at Sudbury are of three types:—

(1) norite containing disseminated sulphides;

(2) massive sulphides containing particles of rock;

(3) footwall quartzite impregnated with sulphides.

The norite which forms the hanging wall is always spotted with sulphides, but there is a sudden passage from this sulphidic norite to the massive ore-body.

Many hypotheses have been advanced to account for the formation of these ore deposits, and the history of the controversy illustrates admirably the difficulty of referring such a complex body to a single cause. The earliest workers in the area considered the deposits to have been formed by concentration of the sulphides on the floor of the sill, either under the operation of Soret's principle or simply by the sinking of the sulphide crystals. But the study of the ore material under the microscope showed that the sulphides were not the first minerals to form in the magma, but the last. Coleman thought that the sulphides separated out as a liquid, which found its way to the floor of the chamber and crystallised there. He pointed out that the ore-bodies often lie in the hollows of the floor, where a liquid would naturally collect. Roberts and Longyear show that some ore-bodies occur on convexities of the floor, but Coleman explains this as a subsequent effect due to faulting.

According to the view of E. Howe and A. M. Bateman, the sulphides were introduced as a separate intrusion after the norite had solidified. Apart from the remarkably patchy nature of the supposed intrusion, this leaves the bulk relation between norite and ore unexplained, and also the widespread occurrence of blebs of ore in the perfectly fresh and unfractured norite. On this view, too, the ore is of magmatic origin, being derived from the same underground reservoir which supplied the norite magma.

C. W. Knight and C. W. Dickson have supposed the ore to be introduced in aqueous solution after the consolidation of the norite. J. W. Gregory also upholds the aqueous origin of the ore. This theory is open to the same objections as the last, and to the additional one that the secondary minerals and vein-stones which are characteristic of aqueous deposits are not at all abundant at Sudbury.

C. F. Tolman and A. F. Rogers have advanced the view that as the crystallisation of the norite progressed, the sulphides were carried outwards by " mineralizers," or escaping magmatic fluids, and deposited along the contact with the underlying rocks, where to some extent they replace both norite and footwall. On this view, the ore is what we have called an internal contact deposit. It is not clear, in this case, why there has been no deposition of ore at the upper as well as the lower contact.

A. Wandke and R. Hoffman admit that little blebs of sulphide occur in the fresh norite, of which they make up from half to one per cent., and they record a zone of this spotted norite, six hundred yards wide, above the main ore-body at the Creighton Mine. In spite of this they reach the same conclusion as E. Howe, that the ore was introduced after the norite had solidified, and that the " ore solutions," derived from the underlying magma reservoir, rose along zones and belts of shattering at the lower margin of the norite sheet.

A. P. Coleman, in a later discussion of the question (1924) adheres to his view that the ore is due to magmatic segregation, but he agrees that " the theory should be widened along the lines suggested by Howe and Bateman, to include the coming in of molten ore along certain channels after the norite had partially consolidated." Writing in 1926 he says " everyone admits that circulating hot water has modified them [the ores], especially in offset deposits, but no hot waters could have distributed the little particles of sulphides through cubic miles of pyrrhotite-

norite, sometimes absolutely fresh and without shearing and fissures. The origin of this part of the ore can be accounted for only by magmatic segregation."

Since the appearance of blebs of ore all through the norite has not been explained by the protagonists of any of the alternative theories, it seems wholly reasonable to claim the norite as the parent of the ore; but the evidence suggests that at least two agencies have combined to produce the workable ore bodies: one that collected the sulphides in the lower part of the eruptive, and another that distributed them, carrying them to some extent out into the country rock. The first may very well have been gravitation, as maintained by Coleman; the second, hot magmatic fluids ("mineralizers") as Tolman and Rogers contend. The suggested injection of "molten sulphides" is discredited by the very high melting-points of these sulphides. J. H. L. Vogt gives 1183° as the melting point of pyrrhotite, 1170° for FeS, and 1130° for Cu_2S. In mutual solution there would be a lowering of the melting point, to an extent that has not been determined.

So far then as the first agency is concerned, the Sudbury ore-deposits may be described as primary segregations from the norite magma; but the operation of the second agency introduces also the characteristic feature of the group of contact deposits.

The copper-nickel deposits of the Insizwa Range, in Griqualand East, South Africa, as described by A. L. du Toit, present in many respects a striking analogy to the Sudbury occurrence. The ore-bearer is a great curved sheet of gabbro from two to three thousand feet thick, intrusive in shales. The rock ranges in composition from normal gabbro to olivine gabbro and olivine norite, with some facies so poor in felspar as to be called picrite. The sheet shows a steady increase in basicity from top to bottom; the lowest horizons contain olivine, while towards the upper contact the rock develops micropegmatitic quartz, and olivine is absent. Here also the gabbro is cut by veins of microgranite. The ore occurs exclusively at the lower contact, where the shale is altered locally to a mica-hornfels; to a small extent this hornfels is impregnated with ore. The principal ores are the same as at Sudbury. Minerals that are characteristic of aqueous deposits, such as quartz, calcite and chlorite, are entirely absent, and every stage is represented between norite with traces of ore and pure ore almost without silicates, consequently the eruptive origin of the deposit is perhaps more clearly shown than is the

case at Sudbury. Nevertheless, T. C. Phemister, after studying a collection of specimens of the Insizwa ore, has maintained that the ores are of hydrothermal origin and replace biotite. It is likely, therefore, that a double process of concentration and rearrangement was operative in this region, just as at Sudbury.

The copper deposits of Little Namaqualand, South Africa, are found in rocks that belong, on the whole, to diorite and norite, but there are also melanocratic types made up almost wholly of hypersthene or hornblende, and extremely leucocratic anorthosites. The biggest ore-bodies have been found in mica-gabbro, as at O'okiep mine, but at Tweefontein the ore-bearer is norite and at Nababeep it is hypersthenite. Olivine is entirely absent from these rocks. The sulphides are bornite and chalcopyrite, and a good deal of magnetite is also present. The ore occurs in irregular bodies and seams, and also disseminated through all the eruptive rocks. The rocks are generally perfectly fresh, and where they make contact with surrounding rocks (various kinds of gneisses and schists) the latter have been impregnated with ore to a distance of a few feet from the contact. The rich bodies of ore have no constant position within the intrusions; they are not especially developed along the contacts. A. W. Rogers, who has described the occurrence, says that "the decisive evidence for the magmatic origin of the sulphides is to be found in their behaviour in the mixed ore-bearers . . . where different but closely related types of rock contain different amounts of sulphides. The content of sulphides in any one of these varieties is fairly constant."

Another deposit of copper, iron and nickel sulphides, which is claimed to be a pure magmatic segregation, occurs in the great norite sheet of the Transvaal. The ores are chiefly pyrrhotite, pentlandite and iron and copper pyrites, and according to P. A. Wagner the deposits take the form of completely isolated masses, composed in part of disseminated sulphides, partly of mottled ore-rock, and partly of massive sulphides. Wagner holds that "droplets of gassy iron-nickel-copper matte separated, at a certain stage in its crystallisation, from the parent norite magma, and were aggregated under the influence of gravity." He believes that the replacement of silicates by sulphides played quite an unimportant part in the formation of the deposits.

The view has frequently been expressed that sulphides and silicates are immiscible in the liquid state, and that deposits such as those of Sudbury, Insizwa, and the western Transvaal are

due to the separation of liquid sulphides (with a little dissolved silicates) from liquid silicates (with a little dissolved sulphides). J. H. L. Vogt has studied the solubility of metallic sulphides in silicate slags; he finds that the sulphides of calcium, manganese, iron and zinc are soluble to the extent of 6 to 8 per cent. at temperatures between 1300° and 1500°, the solubility increasing very rapidly above 1100° and being greater the more basic the slag. The sulphides of copper, lead, silver, nickel and cobalt were found to be considerably less soluble. On cooling these sulphidic slags the sulphides do not separate in the liquid form but crystallise out before the silicates.

J. F. Kemp points out that copper matte settles *quite completely* from a viscous mixture of matte and slag in the forehearth of a furnace, even when it constitutes only five or six per cent. of the mixture.

The solubility of sulphides would seem to be considerably greater in rock magmas than it is in slags. An attractive example, with which we must close this discussion, has been recorded by E. S. Bastin, in Knox County, Maine. He describes a small intrusion of peridotite which has the following composition:— olivine 60, pyrrhotite (with a little nickel and copper sulphide) 22.5, magnetite 10, plagioclase (Ab_1An_1) and hornblende 7.5 per cent. Rounded grains of olivine are enclosed in pyrrhotite, yet the olivine is *perfectly fresh*, which is good proof that the ore was not introduced in solution. Bastin says that "practically all the pyrrhotite is an original crystallisation from the magma and is essentially contemporaneous with the other principal constituents of the rock." The sequence of crystallisation was (1) olivine; (2) olivine and hornblende; (3) pyrrhotite and felspar.

Type (3). Contact Deposits.

Deposits of this type may be closely linked up with those of Type II., as the discussion of the Sudbury ores has shown. In that instance, the segregation of sulphides at the margin of an eruptive mass is associated with a certain amount of replacement and impregnation of the rocks in the contact zone, so that it becomes difficult to hold the two types of deposition quite apart.

The character and extent of a contact deposit are determined by a number of factors, among which, of course, the composition and the volume of the emanation from the magma come first. Similar eruptive rocks do not always yield similar ore-deposits, and a type of rock which in one locality is accompanied by exten-

sive ore-bodies may in another place be barren. The granite batholiths of Norway and Sweden are almost completely free from tin and wolfram, which are among the most characteristic ores of granite in other parts of the world. Again, very different rocks may give rise to identical ore-deposits. V. M. Goldschmidt finds that the contact phenomena—including the contact ore-deposits—in the Christiania district of Norway are independent of the nature of the eruptive, acid granites and basic essexites producing the same effect.

Other important factors are the porosity of the country rocks and their capacity for entering into chemical reaction with the emanation. Tight slates or shales and fine-grained lavas are not easily permeated by emanations, whether liquid or gaseous; and ore-deposits along contacts with such rocks tend to be thin and patchy. On the other hand, if the country rock is capable of reacting with the emanations and forming insoluble and non-volatile compounds, then the bulk of the mineral matter conveyed outwards from the magma will be retained in the contact zone, and an extensive ore-deposit may result. The influence of the character of the country rock is well illustrated where the contact involves several different kinds of rock, such as interbedded limestones and shales. The limestones are then found to be highly altered, silicified and impregnated with ore, while the associated shales are little affected.

Other factors whose effect it is less easy to foresee are the water-content of the invaded rocks, the temperature of the intrusion, and the rate of cooling. Some experiments by E. C. Sullivan, on the separation of the constituents of a solution by a mineral filter, deserve to be mentioned here as they probably have a direct bearing on the production of contact deposits of oxidic ores. Sullivan filtered weak solutions of ferric sulphate through Pasteur filters and found that with repeated filtration the iron content of the solutions was steadily reduced, while the concentration of the acid radicle remained constant. Ferric hydroxide was retained in the pores of the filter, from which, at the same time, a very small quantity of bases was taken up by the solution. The action is explained thus: ferric sulphate is hydrolysed in solution, and the hydroxide is present in the colloidal state; it therefore removed mechanically by the filter.

A most instructive case of a contact deposit in limestone is described by W. Lindgren in the Clifton-Morenci district of Arizona. A great thickness of limestones and shales, ranging

in age from Cambrian to Lower Cretaceous, is invaded by stocks and laccolites, as well as by a network of sheets and dykes, of various kinds of porphyry. The latter rocks are described by Lindgren as granite porphyries, quartz-monzonite porphyries and diorite porphyries, and we must pay some attention to their composition. The granite porphyry has small white felspars, quartz bipyramids, and scales of altered biotite in a fine-grained groundmass of orthoclase, albite and sericite. The ratio of Or : Ab : An is shown to be about 23 : 25 : 1. The " quartz-monzonite porphyry " has insets of orthoclase and zonally built plagioclase, which may be as calcic as labradorite, also quartz and biotite, in a microcrystalline groundmass of quartz, felspar, magnetite and secondary minerals. Lindgren calculates the approximate composition of this rock to be as follows :—quartz 22, orthoclase 16, albite 45, anorthite 10, biotite 6, titanomagnetite 1 ; thus the rock is much more acid than monzonite and should be called granodiorite-porphyry. The diorite-porphyry holds insets of labradorite and hornblende in a scanty groundmass of felspar, quartz and decomposition products. In absence of quantitative details it is difficult to judge how this rock should be classified.

The ore-deposits occur either in the granite and granodiorite-porphyries or else close to their margins, and areas in which there are no intrusions of these rocks are practically barren. It is noteworthy that the diorite-porphyry has had little effect either in altering the limestones or in introducing ore; and it is clearly established that the metamorphic action of the various intrusions is in direct proportion to the quantity of quartz that they contain. The shales and sandstones in the contact zone are baked, and the shales are changed, at the immediate contact, into dense hornfels. The pre-Cambrian granite and the quartzites are unaffected; but wherever limestone enters the contact zone it has been intensely altered through a distance of as much as two thousand feet from the contact. The Longfellow limestone is transformed into a granular rock consisting of garnet, epidote, diopside, magnetite, pyrites, zinc blende and copper pyrites. The Morenci shales are changed to a dense, greenish hornfels with secondary amphibole and a little pyrites and magnetite. The Modoc limestone, which normally holds about 96 per cent. of pure calcium carbonate, has been converted into a massive sheet of lime-iron garnet holding magnetite and copper ore. " This transformation, involving large additions of silica and ferric iron, is very noteworthy, as the evidence is entirely incontrovertible."

The ore-deposits include tabular contact bodies, fissure-veins, and stockworks in the porphyry. The primary ores are pyrites and copper pyrites, with a little zinc blende and molybdenite, but chalcocite and a large number of other primary and secondary minerals are present in addition. The gangue of the veins is quartz, while the deposits in limestone are associated with epidote, magnetite, diopside and tremolite. Lindgren shows that in the porphyry which produced all this metamorphism, the quartz grains are full of enclosures, not exceeding 0.02 mm. in diameter, of salt water containing tiny cubes of salt and crystallites of an opaque or dark red iron mineral, perhaps specularite. The quantity of salt present in these inclusions is far greater than could be dissolved by the water even at boiling point. Thus the eruptive rocks must have crystallised in the presence of strong saline solutions containing iron compounds, and it is believed that these solutions were the media by which iron, silica, sulphur and other bodies were transferred from the eruptive to the limestone.

Other contacts of the same type have been described by J. F. Kemp; in each case a very pure limestone containing little or no alumina and ferric oxide has been converted into a garnet-magnetite rock in which the garnet contains from 10 to 32 per cent. of ferric oxide. At Tamaulipas, Mexico, a streak of garnet was followed from the contact zone into the eruptive rock (granodiorite-porphyry(?)), and when well within the latter the streak opened out into a cavity lined with crystals of orthoclase. "Apparently in this case we have revealed the very supply fissure from which the magma in its cooling stages gave forth the vapours or liquids which produced the zone."

A very similar case was described by A. Bergeat, at Concepcion del Oro, Zacatecas, Mexico, where a stock of granodorite breaks through Jurassic and Cretaceous beds consisting of limestone and marl. The average granodiorite is a pale, porphyritic rock with numerous insets of plagioclase in a ground of quartz and orthoclase, with biotite, generally some pyroxene, and sometimes hornblende. The plagioclase has a well-marked zonal structure, the cores of the crystals having the composition Ab_1An_1 and the mantles Ab_2An_3. The quartz is variable in quantity, and it is full of little enclosures with gas bubbles, isotropic cubes (rock salt?) and opaque crystallites of unknown composition. About its margin the granodiorite passes into syenitic and dioritic facies, with dark bands and streaks. The following contact phenomena are observed:—

(1) Near the margin, the granodiorite holds enclosed masses of garnet and diopside. Sometimes there are simply recrystallised limestone fragments, but at other times the minerals are intergrown with plagioclase, so they must actually have been dissolved and crystallised from the magma. Little garnets with enclosures of diopside, plagioclase and apatite are also strewn through the groundmass of the granodiorite.
(2) Actual solution of limestones is convincingly shown by a dyke, several metres wide, which is composed of acid plagioclase with diopside, garnet, sphene and some orthoclase. It holds about 16 per cent. of lime, or double the amount in normal granodiorite. If about half of this lime is subtracted, and the residue recalculated to 100, the result is close to the composition of the normal granodiorite. It is concluded that about 10 per cent. of limestone has been dissolved by the magma in forming this dyke-rock.
(3) Along the contacts, the limestone has been converted into garnet-rock, and so has the diorite. The latter is changed locally into a fine-grained rock consisting of garnet, diopside, wollastonite, quartz and calcite, but the form of the plagioclase crystals is perfectly preserved, and even their zonal structure is retained in the pseudomorphs, showing that the garnetization took place after the felspar had crystallised. This contact rock contains more than 30 per cent. of lime.
(4) In the limestone, which in its normal state holds a little silica but practically no alumina or iron, an iron-rich garnet has been formed in abundance, as well as diopside, vesuvianite, scapolite and epidote.

Pyrites and pyrrhotite are also universally present in the contact zone. The ore deposits are partly tabular bodies lying along the actual contact of granodiorite with limestone, and partly fissure deposits running out at right angles to the contact. The first type of deposit contains copper pyrites, with magnetite, iron pyrites, a little zinc blende and quartz, but no wollastonite. In the fissures, which carry ore up to a distance of about a hundred metres from the contact, magnetite is absent and pyrites scarce, but zinc blende is common, arsenical tetrahedrite is found, and quartz and wollastonite are the essential veinstones.

Bergeat concludes that the emanations which deposited the ore, and formed garnet rocks at the expense of both limestone and diorite, must have come from still fluid magma at a greater depth. On account of the presence of wollastonite and the total

absence of hydrous silicates, he ascribes the action to hot gases rather than to aqueous solutions.

V. M. Goldschmidt has given a very complete description of contact deposits in limestone in Norway. The Christiania district is very favourable for the study of contact metamorphism, since regional metamorphism is absent, thus there is no confusion of effects due to different causes. The eruptive rocks, which have all been described by W. C. Brögger, range from melanocratic gabbros and pyroxenites to monzonites, akerites, syenites, foyaites, and granites; yet Goldschmidt shows that the contact effects produced by the melanocratic rocks are indistinguishable from those seen at the granite and syenite contacts, and the same thing is true of the ore-deposits. The Silurian shales are baked and recrystallised, with production of coarse-grained biotite-hornfels, often carrying large crystals of orthoclase. The sandstones pass with little change into quartzites. The limestones give lime-silicate rocks ("skarn") containing especially andradite (lime-iron garnet) and hedenbergite (lime-iron pyroxene), for the formation of which one must assume an addition of iron and silica from the magma.

The skarn and the ores are closely connected, and commonly interbedded. Hematite, bismuthine and molybdenite are generally older than the silicates with which they are intergrown; magnetite, pyrite and pyrrhotite are partly older and partly younger; and other sulphides such as blende, galena and chalcopyrite are younger than the silicates of the skarn. Goldschmidt describes a blende-andradite rock consisting of well-formed crystals of andradite in a groundmass of blende, fluorite and albite. Iron is by far the most abundant of the metals introduced into the contact zones, but the greater part of it is in lime-iron silicates, not in ores. Zinc comes next in abundance, then copper, lead and manganese. Goldschmidt suggests that the iron was introduced in the gaseous state as chloride or fluoride, and the silica also as a halogen compound, in the earlier stages at least. There would be no reaction between these substances and the constituents of shales or sandstones, but with limestone the following reactions are possible:—

$$2\ FeF_3 + 3\ CaCO_3 = Fe_2O_3 + 3\ CaF_2 + 3\ CO_2$$
(hematite) (fluorite).

$$2\ Fe\ Cl_3 + 3\ CaCO_3 = Fe_2O_3 + 3\ CaCl_2 + 3\ CO_2$$

In the latter case the calcium chloride is likely to be fixed eventually in scapolite and so retained in the contact zone.

A similar reaction between silicon fluoride and limestone may yield wollastonite

$$SiF_4 + 3\ CaCO_3 = 2\ CaF_2 + CaSiO_3 + 3\ CO_2$$
(fluorite) (wollastonite)

From this, again, andradite can be derived as follows :—

$$3\ CaSiO_3 + Fe_2O_3 = Ca_3\ Fe_2(SiO_4)_3$$

An example of a contact deposit of pure magnetite is given by A. Lacroix, at Boutadiol in the eastern Pyrenees. The ore is deposited along the actual contact of granite and limestone, and it also forms veinlets in both rocks. It is coarsely crystalline, with cavities which are lined with perfect rhombic dodecahedrons, and it is locally associated with garnet, pyroxene and amphibole. These silicates are of the same kind as those developed in the limestone further away from the contact, but they are much richer in iron; thus the garnet is melanite instead of grossularite; the pyroxene, hedenbergite instead of diopside; the amphibole, a dark ferruginous hornblende instead of the usual pale green variety. Lacroix has observed that the mineralogical composition of the granite always varies according to the chemical character of the country rocks, and that the granite in the neighbourhood of the magnetite deposits shows no local peculiarity; hence he concludes that the iron oxide was not an original constituent of the limestone but was introduced by emanations from the magma.

O. Stützer in Canada and N. Fukuchi in Japan have shown a progressive decrease in the silica content of the successive zones of mineralization between granitic rock and limestone. At the Copper King Mine, in the White Horse district, Yukon, the ores lie at the margin of a tonalite, and the successive zones are as follows :—(1) tonalite, (2) garnet-pyroxene rock with ore, (3) wollastonite rock with ore, (4) limestone. In the Japanese case described by Fukuchi the succession is (1) granite, (2) hedenbergite zone, (3) garnet-ore zone, (4) wollastonite zone (5) limestone. In these instances we may see proof positive not only of a siliceous emanation from the magma, but of the influence of varying temperature conditions upon the type of mineralization produced by the emanation in its reaction with limestone. The ore of the Copper King is bornite with a little chalcopyrite, and it is interesting to note that the tonalite has drusy cavities lined with quartz and felspar and holding a core of felspar, apatite and bornite, the latter being the last to crystallise.

An excellent illustration of the influence of the country rock on the nature and extent of an ore deposit is afforded by the magnetite contact ores of Shasta County, California, described by B. Prescott. Granodorite, andesite, shale and limestone all come in turn into contact with a quartz-augite diorite (tonalite?) which is the ore-bringer. Bodies of magnetite are developed between the diorite and *all* the country rocks, but those at the andesite and shale contacts are small and irregular; at the granodiorite contact the ore deposits are up to 50 feet thick and several hundred feet long; and at the limestone contacts the ore bodies have still greater dimensions. The limestone is a very pure one, holding 96 per cent. of calcium carbonate, yet lime-iron garnet (andradite) and lime-iron pyroxene (hedenbergite) as well as ilvaite, have been formed from it; and magnetite, chalcopyrite, and other sulphides have been introduced from the magma. The available silica in the limestone is less than 3 per cent. of the amount required for the production of these silicates, and the iron less than one per cent., and traces of manganese and chromium are present in the contact minerals although totally absent from the limestone. The conclusion is irresistible that all these substances were introduced by the magma, and that the limestone received the bulk of them because its porosity and capability for reaction were greater than those of the other contact rocks.

The influence of the country rock is again brought out by C. W. Wright in his study of the copper deposits of the Kasaan Peninsula, the principal copper producing area of Alaska. The country rocks in this case are greenstones and greenstone tuffs, sandstones, conglomerates and limestone, and the ore-bringers are granodorite and syenite. The ores are chalcopyrite and magnetite, sometimes the one being predominant, sometimes the other. Where the contact is in greenstone tuff the ore is associated with hornblende, epidote and orthoclase; where in limestone, with garnet, epidote and calcite. There is no secondary alteration whatever.

J. E. Spurr, G. H. Garrey and C. N. Fenner have made a close study of the contact phenomena at the Dolores Mine, San Luis Potosi, Mexico. The intrusive rock is granodiorite, the intruded rock limestone, and in the contact aureole a number of lime-aluminium-iron silicates and other minerals have been developed in a definite order, as follows: (1) aluminous pyroxenes, (2) aluminous garnets, (3) wollastonite, (4) iron pyroxene (hedenbergite), (5) iron garnet (andradite), (6) fluorite, quartz and

sulphides, (7) sulphides, (8) calcite. At each stage the previously formed minerals were attacked and replaced by the newcomers, showing that the sequence is due to changing solutions whose composition corresponded to that of the successively deposited minerals. These solutions carried at various stages (1) alumina and silica, (2) silica, (3) silica and iron. The ores too arrived in a definite order, thus (1) chalcopyrite and pyrite, (2) arsenopyrite, (3) pyrite and pyrrhotite, (4) blende, (5) galena. Both the limestone and the eruptive rock itself have been attacked by these changing solutions, so that the deposit belongs partly to the internal and partly to the external type.

Spurr emphasises the view that contact deposits such as these require prolonged periods of time for their formation, which continues long after the eruptive rock has completely solidified; and that the solutions that generate such deposits come from the deeper zones of the magma reservoir and are not simply "squeezed out" of the portion of the magma adjacent to the contact. This view helps one to understand the uniformity of the contact deposits formed about very different kinds of rock, as in the Christiania district, already described.

A variation of type is exhibited by the contact ores of Glamorgan, Ontario, described by W. G. Foye. Here the country rock is a great gabbro laccolite intrusive in limestone, and the ore-bringer is foyaite, which was intruded about and beneath the gabbro. The gabbro has normally a contact aureole of garnet-diopside rock, but wherever the foyaite is found beneath it this contact rock disappears and is replaced by a rock consisting of calcite, scapolite, actinolite, diopside and plagioclase, above which the *gabbro itself* has been scapolitised. Titaniferous magnetite occurs along the lower contact of the gabbro, between it and the nepheline rock, and is associated with scapolite, apatite, pyrrhotite and hornblende. It is held that the gases given off by the foyaite at the time of its intrusion collected beneath the gabbro laccolite, introducing and depositing iron oxide, while the chlorine and other gases set free attacked the felspar of the gabbro, converting it to scapolite. This view is in full agreement with that expressed by V. M. Goldschmidt for the Christiania district.

The study of contact deposits such as these gives the strongest support to the view already expressed regarding the importance of the fugitive constituents of the magma. The phenomena that we

have been discussing indicate an extensive transference of silica, alumina, iron, copper and other heavy metals, along with chlorine, fluorine, sulphur and arsenic, from the magma to the surrounding rocks. *There is no logical source for these substances except the magma itself.* Possibly some part of the material travelled out as a gaseous emanation, but the bulk of the evidence points to water as the vehicle that effected the transference. We have already discussed the matter in Chapter III.

Type (4). Self-Replacements Along Pipes and Fissures. These are the " pneumatolytic " deposits of some writers, and they are generally regarded as a different type from the contact deposits; yet they have much in common with the internal contact deposits and may merge into the latter, or the fissure deposits within the eruptive may pass into ordinary contact deposits in the country rock.

C. Reid and J. S. Flett recognise three types of " pneumatolysis " in the granites of Cornwall, leading to the production of tourmaline-rock, greisen, and chinastone respectively. The tourmaline rocks often form a marginal fringe around the granite from which they have been derived. In these rocks the tourmaline replaces both felspar and mica. The form of the original felspar crystals is sometimes preserved, and every stage of the transformation from felspar to tourmaline can be observed in the field.

In the second type, tourmaline is nearly absent, and the rock consists essentially of quartz and white mica. To such rocks the name " greisen " is applied. In Cornwall the greisens are generally developed as selvages on either side of fissures, and they carry small quantities of topaz, tourmaline, apatite and cassiterite. In the greisen of Saxony topaz becomes an essential constituent.

The third type of alteration in the granites of Cornwall leads to the production of kaolin or china clay. The deposits of this mineral generally occupy very irregular pipes within the granite; more often situated centrally than marginally. The quartz and much of the mica of the granite remain, but the felspar is converted into kaolin. It is unusual for either fluorine minerals or ores to be present in these deposits. Flett and Reid find no evidence to show that any element has been introduced into the rock during kaolinisation; on the contrary, there seems to have

been a loss of all constituents except alumina. Kaolinisation is generally supposed to take place at a lower temperature than the production of tourmaline or topaz, and there seems to be no necessity to assume the action of any stronger reagents than water and carbonic acid in the process. There is a very marked relation between the distribution of tin lodes and that of kaolin deposits in Cornwall. (*Fig.* 41.)

The formation of topaz-rock at the expense of granite finds its typical illustration at Schneckenstein, in Saxony. Specimens of the topaz rocks of this region are to be found in every mineral cabinet. The Eibenstock granite is cut by dykes of granite-porphyry and microgranite, which also run out into the surrounding beds. The dykes are deeply altered, the felspar being mostly replaced by topaz, with sometimes a little tourmaline and traces of cassiterite. For such quartz-topaz rocks the name greisen is commonly used, but some distinction should be made between the quartz-topaz type of greisen and the quartz-mica greisens of Cornwall, which seldom contain topaz. Quartz-topaz greisens containing tinstone occur at Gunong Bakau, in the Federated Malay States. J. B. Scrivenor, who has described these rocks, regards them as unaltered eruptive rocks, but this improbable view is opposed by W. R. Jones.

At Mount Bischoff, in Tasmania, the alteration of granite-porphyry dykes to greisen is finely illustrated. The dykes are met in their unaltered condition among the Palæozoic strata that form the hill, and as they are traced towards the summit they pass rapidly into greisens rich in topaz and tourmaline. W. von Fircks notes that the rocks that are richest in topaz are also very rich in cassiterite, which is almost absent from the varieties rich in tourmaline. Other minerals present in these greisens are fluorite, mispickel, pyrite, pyrrhotite and secondary quartz.

Another type of alteration is shown in the Federation Mine at South Heemskirk, Tasmania. According to L. L. Waterhouse, the ore-body occupies a pipe in the Heemskirk granite. In cross-section the pipe is roughly oval, and its dip varies from vertical to nearly horizontal. At the surface the diameter was twenty-five by fifteen feet, but when followed downwards the pipe tapered out to five feet by one in a depth of 115 feet. In one part of its course a branch pipe was thrown out horizontally. The filling of this pipe consisted mainly of greenish coloured, waxy looking, massive mica, holding cassiterite and pyrites. Between this and the normal granite was a zone of harder material containing quartz and tourmaline, and this in turn graded into the granite.

FIG. 41. Geological map of the St. Austell granite mass, Cornwall, showing the distribution of china-clay areas (dotted) and tin lodes (black lines). (After D. A. MacAlister.)

Pipe deposits apparently similar to the above have been described in New South Wales by L. A. Cotton and E. C. Andrews. The latter describes greisens, tourmaline greisens, and pipes in the granites of the New England plateau. At Giants' Den he notes that a large area of greisen is cut by quartz veins carrying tinstone, tourmaline and topaz. On the Mole tableland the granite is transformed to greisen on either side of fissures, just as in Cornwall, but the alteration seems to have been much more widespread, sometimes extending more than a hundred feet

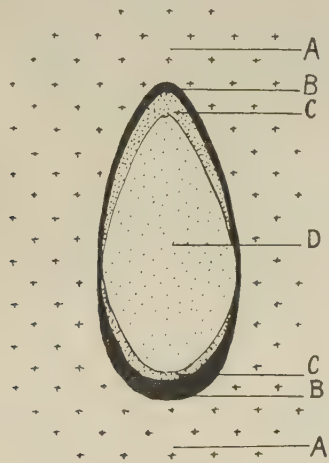

FIG. 42. Cross-section of a tin-bearing pipe in granite, Groenfontein, Transvaal. (After Kynaston and Mellor.)

A, normal granite. B, tourmaline-rock. C, tinstone. D, altered granite containing five per cent. of tinstone. Greatest diameter of pipe, 16 feet.

from the fissure. In the same region many pipe deposits have been located, which yield molybdenite, bismuth and bismuthine in addition to cassiterite. In a pipe at Kingsgate, " the central gangue is quartz, often magnificently crystallised, while around the ore and crystallised quartz masses a hard, vitreous, granular quartz is often observable. This passes peripherally into masses of granular quartz and aggregates of white and yellow mica; this in turn merges into quartz and cloudy felspars, and this finally into ordinary granite."

A small pipe at Tingha was subcircular in horizontal section, with a diameter of four feet at the surface and an average inclination of 80° to the horizon. "Traced along the greater diameter the pipe assumes a blunt wedge shape, and passes into a mere joint, less than one-twentieth of an inch in width. The contents

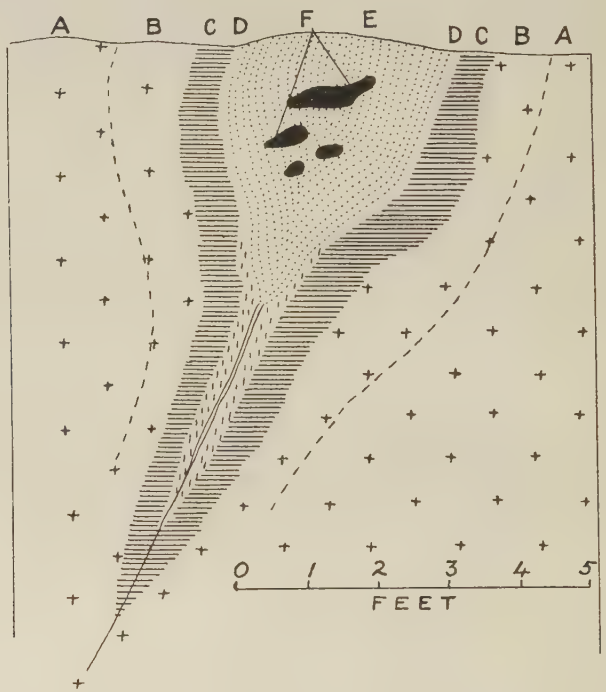

FIG. 43. Section of ore-body at Groenvlei, Transvaal, after Kynaston and Mellor.

A, unaltered granite. B, slightly altered granite with fluorspar. C, granite with sericitized felspar. D, narrow zone of white quartz, with tourmaline in lower portion. E, ore-body (cassiterite, quartz, tourmaline). F, irregular patches of cherty silica.

of this pipe were felspar and sericite with tinstone, passing outward through zones of less sericite into normal hornblendic granite." Andrews finds that these pipes lie at the intersections of two sets of joints, and holds that the deposits arose by a replacement of granite by solutions and gases that rose along the joint plane, especially at their intersections.

At Inverell, New South Wales, greisen lies along the margins of the granite. It contains much tin and topaz, and some wolfram. The granite is extensively tourmalinised.

Typical greisen is not common in South Africa. H. Merensky records irregular bodies of quartz-topaz greisen carrying cassiterite at Vlaklaagte, Transvaal. These bodies have yielded up to 40 per cent. of tinstone, but the ore is very patchy. The derivation of quartz-mica greisens, holding wolfram and scheelite, from aplite, porphyry and pegmatite dykes is recorded by the Geological Survey of Southern Rhodesia at Essexvale. Tin-bearing pipes of great richness occur in granite in the Waterberg district of the Transvaal, and have been described by H. Kynaston and E. T. Mellor. (*Figs.* 42, 43.)

Type (5). Ore Deposits in Aplites and Pegmatites.

Aplite and pegmatite are relative terms, and indicate respectively rocks of finer or coarser grain as compared with the texture of the larger eruptive masses from which they have been derived. They form veins, pockets and irregular bodies within eruptive rocks of all kinds, but especially the more siliceous, and also run out into the country in the form of sheets and dykes. One and the same vein or dyke may show both aplitic and pegmatitic variations, the former sometimes forming the margin and the latter the central portion of a vein. In composition aplites and pegmatites show a wide range, but the great majority of them consist of an alkali felspar (orthoclase, microcline, albite, or oligoclase) together with quartz and white or black mica. Many pegmatites contain almost nothing else, but others are remarkable for the great variety of uncommon minerals which they yield. Aplites seldom contain any unusual minerals, and it is with the pegmatites that we shall mainly be concerned.

To earn the name of pegmatite, it is only necessary that the dyke rock should be distinctly coarser in grain than the rock it traverses; thus a segregation vein with an average grain of only a few millimetres may be a real pegmatite with respect to a more fine textured rock in which it occurs. But in most pegmatites, and in all of economic importance, the texture is very coarse indeed, the average grain being expressible in feet and inches. Individual crystals are sometimes described as "of the size of a cottage," and in the Ural Mountains a quarry is said to have been opened within a single felspar crystal. In the Etta pegmatite

mine in South Dakota giant crystals of spodumene were found, the greatest of which measured thirty-six feet by six by three. In some of the pegmatites of Maine there are single masses of felspar and quartz twenty feet long, and beryl crystals of " the diameter of a hogshead." In the pegmatites of the Leydsdorp fields, Transvaal, crystals of mica have been found up to five feet in diameter and several tons in weight; and at Mount Carbine, Queensland, a block of wolfram weighing six tons has been recorded.

Pegmatite veins within eruptive rocks sometimes have sharp boundaries, but more often they pass over quite gradually into the surrounding rock, showing that they are really segregations from the magma and not independent intrusions. The pegmatites in granite often contain the same assemblage of minerals as the granites themselves, but in less acid rocks such as syenite, diorite and gabbro the pegmatites are generally more siliceous and more leucocratic than the rocks that contain them. The crystallisation of the granite pegmatites took place at a comparatively low temperature, which the experiments of F. E. Wright and E. S. Larsen place in the neighbourhood of 575°, or not far above that temperature.

The order of crystallisation of the constituents of pegmatites is rather irregular, and some minerals seem to have crystallised in two stages. Those of the earlier stage are intergrown with the felspars and other silicates, or are enclosed by them, while those of the later stage are implanted upon the walls of cavities and attached to the faces of earlier crystals. The former were generated by the magma itself, the latter probably by aqueous solutions representing the " dregs " of the magma. Some pegmatites are particularly rich in minerals containing fluorine, boron, chlorine, lithium, phosphoric acid and hydroxyl, and the rare metals cerium, lanthanum, didymium, thorium, zirconium, yttrium, niobium, tantalum, beryllium, uranium, etc.

The valuable minerals that are extracted from pegmatites may be classified roughly as metallic ores, gems, and other useful minerals. Under the latter heading are included quartz itself, which is used in making fused silica ware, and felspar, used for pottery and agricultural purposes and also as a flux in metallurgy. The pale-coloured micas are widely used as electrical insulators and for stove and lamp windows; they are won in large plates from pegmatites in Canada, India, Ceylon, and South and East Africa. These minerals may be regarded as the normal con-

stituents of pegmatites, and the other occurrences that we have to record here as extraordinary developments.

Magnetite is an almost constant accessory constituent of pegmatites, but occasionally it occurs in sufficient quantity to have been the cause of sporadic mining operations. Thus the granite of Georgetown, Colorado, contains pegmatites that carry magnetite and pyrite in addition to quartz, felspar and white and black mica; locally the magnetite is so abundant as to make up nearly half of the rock (Spurr and Garrey). At Lyon Mountain, New York, magnetite has been mined on a small scale in pegmatite and silexite (W. J. Miller); and at Glamorgan, Ontario, crystals a foot and more in diameter are recorded in granite pegmatites (Adams and Barlow).

Apatite is another accessory mineral of granites and pegmatites that occasionally appears in sufficient quantity to repay extraction. A small production has been obtained from pegmatites in Canada and Norway.

Corundum is perhaps the most important of all the minerals occurring in this way. It frequents a class of felspathic rocks and pegmatites from which quartz is almost always absent, and dark minerals—biotite and hornblende—are much reduced in amount. The felspar may range from orthoclase and albite (as at Craigmont, Ontario) to oligoclase (Plumas County, California), andesine (Dungannon, Ontario), bytownite (Lanark-Frontenac) and anorthite (Seine River). The representative pegmatite of Craigmont holds an average amount of 34 per cent. of corundum, rising to as much as 75 per cent.; the minerals associated with it are albite, orthoclase, biotite muscovite (see page 240). The dykes may be as much as 18 feet wide, and they grade imperceptibly into the surrounding syenite or foyaite (A. E. Barlow).

At Kyschtym, Russia, corundum occurs in rocks of low silica content, accompanied by anorthite, biotite, spinel, zircon and apatite (page 241). The more coarse-grained rocks hold only corundum and anorthite, or spinel and anorthite. Corundum pegmatites of the Ilmen Mountains have as their felspar an orthoclase-albite microperthite (J. Morozewicz). At Coimbatore, Madras, the matrix is an alkaline syenite and its pegmatites (T. H. Holland).

The important corundum deposits of the Transvaal occur in andesine-biotite pegmatites; they were described on page 241.

Cassiterite and *wolfram* occur not infrequently in the pegmatites of certain granites, quartz being invariably associated with

them. Well known localities for one or both of these minerals are the Black Hills, Dakota; Gaffney, S. Carolina; Tavoy, Burma; Meru, Perak; New England, New South Wales; Carrock Fell, Cumberland; Finbo, Sweden; Ivigtut, Greenland; Omaruru, South West Africa. The deposits in pegmatite seldom repay exploitation except when they occur in conjunction with richer quartz-veins, as at the Black Hills and Tavoy, or with eluvial deposits, as at Gaffney. The ore is generally found in quartz-rich shoots lying either centrally or along one wall of the pegmatite vein. As a rule, the more felspar the less ore, and many pegmatites pass along their strike into pure quartz veins where the ore is considerably enriched. Useful summaries of the occurrences of tinstone and wolfram in pegmatite are given by F. L. Hess and W. R. Jones.

Molybdenite is mined at Catherine Hill, Maine, where it forms a constituent of quartzose pegmatites in granite. The ore occurs in scales and flakes up to an inch in diameter. Most of it is in or within a few inches of the pegmatite veins, but some of it seems to be an original constituent of the granite. The molybdenite crystallised late and encloses crystals of albite and orthoclase (W. H. Emmons). There are entirely similar occurrences in Nova Scotia, Quebec and Ontario.

Other sulphides. Minor occurrences of sulphides and arsenides of copper, lead, zinc and iron in pegmatites are reported from many localities, but they rarely have any economic value. Quartz-oligoclase pegmatites at Romsaas, Norway, contain chalcopyrite and nickeliferous pyrrhotite, and have been mined for these ores. Bornite occurs in pegmatites at Yale, British Columbia, and at the Khan Mine in South West Africa, which furnishes one of the most important examples of this type of deposit. The pegmatite dyke, which does not exceed seven feet in width and is generally narrower than that, carries bornite, with smaller quantities of other copper ores, in addition to felspar, quartz, pyroxene and sphene. According to O. Stützer, the bornite is an original constituent of the rock, and was the last of the magmatic minerals to crystallise.

Rare-Earth minerals. Minerals containing the rare metals cerium, yttrium, thorium, niobium, etc., are extracted from granite and syenite pegmatites at Austin, Texas; Stoneham and other localities in Maine; the Black Hills, Dakota; Hitterö, Norway; Ytterby, Sweden; and elsewhere. Among these minerals are columbite, tantalite, thorite, monazite, gadolinite, fergusonite,

xenotime, yttrialite, allanite and polycrase. Masses of tantalite up to 600 lbs. in weight were got at Etta Knob, Dakota. Pegmatites furnish also the lithia minerals spodumene, lepidolite and amblygonite.

Gemstones. Many gem minerals have their home in pegmatites. Such are beryl and its green variety, emerald; green and pink tourmaline; kunzite and hiddenite, the coloured varieties of spodumene; sapphire and chrysoberyl; topaz, some kinds of garnet, amethyst, and rose and smoky quartz. Notable localities are Madagascar; Pala, California; Cleveland, N. Carolina; and many districts in Maine.

Type (6). Ore Deposits in Quartz Veins.

We have already seen that in many cases dykes of pegmatite can be traced along their strike into pure quartz veins. There is therefore no sharp distinction between deposits of the present type and those of type (5). Any ores that may be present in a pegmatite or aplite nearly always continue into, and often become more abundant in, the associated quartz veins Thus the pegmatites of Carrock Fell, Cumberland, contain a little wolfram which increases in amount as the felspar content diminishes (A. Finlayson). At Tavoy, Burma, according to J. C. Brown, there are cases where wolfram- and cassiterite-bearing pegmatites pass in a short distance along their strike into pure quartz veins with the same ores. J. E. Spurr states that the alaskite of Silver Peak, Nevada, grades into pure quartz bodies, and with the dwindling of the felspar the gold content increases rapidly. Similarly at Berezovsk, Ural Mountains, gold is concentrated in quartz veins that fill contraction fissures in aplite. In the Black Hills, Dakota, the pegmatites hold tin and tantalite; the latter mineral is absent from the associated quartz veins, but tin and wolfram are present in them. Both wolfram and molybdenite show a preference for the more quartzose phases of pegmatites.

Although quartz is by far the commonest eruptive veinstone, it is not the only one. In the Onaping area of Canada, aplite veins hold a little calcite and pass over into veins of quartz and calcite containing silver and cobalt ores. The great pegmatite that contains the cryolite deposit of Ivigtut, Greenland, is at its margin an ordinary quartz-felspar pegmatite carrying only a little cryolite and ores (sulphides, cassiterite, wolfram and siderite): the central portion is a mass of nearly clean cryolite holding a

few per cent. of quartz, siderite and sulphides. These occurrences serve further to illustrate the point that the transition from pegmatite to veinstone may take place *from the walls to the centre* of a large body of pegmatite. This central position of the veinstone is well shown by the pegmatite bodies in the granite of Quincy, Massachusetts, of which C. H. Warren and C. Palache write that they "take the form of rudely cylindrical masses of considerable size, entirely enclosed in the granite. In mineral composition they are closely similar to the granite, the essential minerals being quartz, alkali-felspar, riebeckite and ægirine; accessory minerals so far identified are fluorite, parisite, octahedrite, ilmenite, wulfenite, and the sulphides molybdenite, galena, sphalerite and chalcopyrite. The pegmatites exhibit a certain symmetry of structure. Fine graphic granite forms a marginal band, succeeded centrally by a zone of coarse granitic texture made up of quartz, felspar, riebeckite and soda-pyroxene. As a rule this zone graduates into almost pure massive quartz, sometimes containing sulphides."

It is not always easy to distinguish between veins of eruptive origin and others formed by lateral secretion after the close of the eruptive period. In the latter case ground water is the active agent, and its operation is generally marked by more or less pronounced decomposition of the rock. Sericite, or fine scaly white mica, and various clayey substances akin to kaolin are formed from alkali felspar, while lime felspars alter to calcite and epidote, and ferromagnesian minerals especially to limonite, chlorite and saponite. The alteration increases in intensity as the vein is approached, and on either wall there may be a clay-like selvage of highly decomposed rock. The association of the ore with such soft, greasy and scaly minerals, all of which are highly hydrated, is generally indicative of the action of ground water.

The vein deposits with which we are here concerned are associated with the closing stages of consolidation of eruptive magmas; they may be in part contemporaneous with the period of pegmatite and aplite formation, but in general it is probable that they represent a slightly later stage, corresponding to a temperature well under 500°. The veins may grade into pegmatite, as in the case of the Quincy masses, or they may show sharp walls, the veinstuff being "frozen on" to the country without any selvage. Hydrous minerals such as those named above are typically absent, but quartz, calcite and fluorite are common and tourmaline is not unusual.

The list of minerals occurring in eruptive veins is a long one; it includes gold, tinstone, magnetite, wolfram and scheelite, bismuth and bismuthine, molybdenite, and many other sulphides and arsenides; besides secondary oxides and hydroxides, carbonates and phosphates formed by the alteration of the primary minerals of the lodes.

The tin and copper lodes of Cornwall have been described repeatedly. The lodes occur in granites and contact-altered Palæozoic slates; in the latter case the direction of the lodes is generally parallel to the cleavage of the slates. The deposits range from simple fissure veins and stockworks, both in granite and in slate, to complex mineralised breccias and conglomerates consisting of belts of shattered rock cemented by ore. Many of the fissures are actual faults. In nearly all cases there has been extensive alteration, silicification or impregnation of the country rock, which is often mined together with the veinstuff. Quartz, tinstone and wolfram generally lie against the walls of the veins, while the sulphides, along with quartz and fluorspar and epidote, occur interiorly. Speaking generally, the lodes within the granite are richest in tin, those in the slate richest in copper, while silver-lead veins occur far out beyond the contact zones and their connection with the granite intrusions is not capable of direct proof. Whenever a tin-copper lode has been followed downward to a sufficient depth, it ceases to carry copper and becomes a pure tin lode. Similarly, some of the copper lodes, and these generally the richest, have a capping of zinc blende. E. H. Davison finds that the order of formation of the minerals in the Cornish lodes was

(1) quartz
(2) cassiterite
(3) tourmaline, chlorite
(4) wolfram
(5) copper pyrites
(6) iron pyrites
(7) zinc blende, quartz, fluorspar
(8) siderite, galena.

A similar areal distribution of the different ores around a granite stock is well illustrated in the Zeehan field, Tasmania, described by W. H. Twelvetrees and L. K. Ward. These geologists distinguish four successive zones of deposition around the margin of the Heemskirk granite, as follows:—

A. Granite zone. Tin lodes with tourmaline, pyrite, wolfram, bismuth and molybdenite.

B. Contact metamorphic zone. A typical contact deposit with magnetite in a gangue of calcium silicates such as diopside, epidote, garnet and vesuvianite. The tin lodes extend a little way into this zone, and cassiterite is rarely admixed with magnetite.

C. Transmetamorphic zone.

(1) Pyritic belt. Chalcopyrite, stannite and galena lodes with a gangue of siderite.

(2) Sideritic belt. Galena-tetrahedrite-pyrargyrite lodes with a gangue of quartz.

Twelvetrees and Ward believe that the above succession " is due to the effect of differing physical conditions in causing the precipitation of different assemblages of minerals from the same metalliferous solutions according to the distance from the magmatic hearth, and that if a lode typical of the sideritic belt were followed downwards towards its source, it would gradually change its mineral character in such a manner that it would become in turn characteristic of the pyritic belt and then of the contact metamorphic belt. There are even indications that the contact metamorphic type may be connected with those of the granite zone, but no direct evidence bearing on this matter was obtained."

Within the Heemskirk granite, according to L. L. Waterhouse, the tinstone occurs in simple veins with walls of comby quartz and a central seam of tourmaline and cassiterite, carrying also small quantities of bismuthine, wolfram, molybdenite and fluorspar. Sometimes these veins pass out into the sedimentary rocks, and then the tourmaline decreases and the vein eventually becomes a pure quartz reef. In another type there is a gangue of quartz, dolomite, tourmaline, chlorite, epidote and fluorspar, and the ores are pyrrhotite, pyrite, arsenopyrite, chalcopyrite and other sulphides, with wolfram and cassiterite or stannite.

In the New England mining district of New South Wales, E. C. Andrews finds that tin and wolfram occur in one set of veins and molybdenite and bismuth in another set, from which tourmaline, topaz, beryl and rutile are typically absent. The tin-wolfram granites have from 75 to 79 per cent. of silica and the molybdenum-bismuth granites from 72 to 74 per cent. The molybdenite deposits are almost always confined within the

margin of the granite, while the tin-wolfram lodes continue a little way into the country.

Molybdenite occurs widely in quartz veins in Eastern Canada; thus on Indian Peninsula, Quebec, molybdenite and bismuthine are associated with pyrite and fluorite in quartz veins in granite; and at Romaine comparatively large plates of molybdenite, up to 12 inches broad and a quarter of an inch thick, were got from a quartz vein of about a foot in width cutting a garnet mica gneiss. In New Brunswick molybdenite and wolfram occur together in quartz veins near a granite contact.

Although the crystallisation of sulphides is in general later than that of cassiterite, molybdenite does not always follow that rule. At Tavoy, Burma, according to J. C. Brown, the order of deposition of the ores is as follows:—molybdenite, wolfram, cassiterite, bismuth, bismuthine, chalcopyrite, arsenopyrite, galena, blende. The Tavoy lodes always carry sulphides, and tourmaline and topaz are typically absent, and even fluorite is scarce. The lodes of the Mergin and Thaton districts, however, contain tourmaline. The tin-wolfram lodes of Potosi, Bolivia, are like those of Tavoy in holding large quantities of sulphides and being almost free from tourmaline and fluorite. The sulphides include those of silver, copper, antimony, bismuth, lead and germanium, with quartz as gangue (G. Steinmann, A. W. Stelzner, W. R. Rumbold).

A very important and widespread type of deposit belonging to the class we are now considering is that of the gold-quartz veins. Many of the occurrences mentioned above show a small content of gold; such are the quartz veins near Camborne and Falmouth in Cornwall; and there is quite a distinct group of gold-wolfram-quartz-veins, as for example at Boulder and Leadville, Colorado. At Berezovsk, Ural Mountains, gold occurs along with tourmaline in quartz-veins which cut across aplite dykes; these "ladder-veins" are found only in the aplites, where they fill contraction fissures, and they scarcely penetrate the country rock at all (R. Beck).

At Silver Peak, Nevada, according to J. E. Spurr, granite passes locally into alaskite or granite-aplite, and that again into pure quartz bodies which contain gold and sulphides (galena, arsenopyrite); the gold content waxes rapidly as the felspar dwindles and disappears.

Another type of eruptive vein deposit is illustrated by the cobalt-silver ores of Ontario. These ores occur in calcite veins

filling fissures in thick sills of quartz-dolerite (diabase), and they seldom pass out into the country rock. The veins are thin, mostly less than a foot wide, and some have been traced for as much as 300—400 feet. The ores are native silver, smaltite, niccolite and chalcopyrite, and the gangue calcite and quartz. Other minerals occasionally present are native bismuth, pyrite, specularite, stibnite and galena. The order of deposition is (1) quartz, (2) chalcopyrite, galena, and specularite, (3) smaltite and niccolite, (4) calcite, (5) silver, (6) bismuth. W. H. Collins notes that a small amount of chalcopyrite is disseminated through the dolerite and associated aplite dykes, and calcite also occurs both in dolerite and aplite; further, that in a few cases the aplite dykes can be traced into calcite veins. Hence Collins concludes that the ore-bearing veins are just end products of the differentiation of the dolerite magma. It is remarkable that adjacent sills of quartz-norite, differing from the dolerite only in respect of the single mineral hypersthene, contain no such ore-bodies.

With this we must conclude our study of the eruptive ore-deposits. There is no doubt that there are many deposits besides those described here, which owe their formation to emanations from an underlying eruptive body; indeed it is generally believed that the great majority of metalliferous lodes are directly or indirectly connected with intrusions of eruptive rock. But with increasing distance from the source, it becomes more and more difficult to prove the connection, and to separate the effects which may reasonably be ascribed to magmatic fluids from those due to ground water.

REFERENCES.

Andrews, E. C.—Records Geol. Survey New S. Wales, 1905, 1907.
Adams, F. D. and Barlow, A. E.—Canada, Geol. Survey, Mem. 6, 1910.
Barlow, A. E.—Canada, Geol. Survey, Mem. 57, 1915.
Bastin, E. S.—(Pegmatites) U.S. Geol. Survey, Bull. 445, 1911.
do. —(Peridotite) Jour. Geol., 1908, *124*.
Bateman, A. M.—Economic Geology, 1917, *391*.
Beck, R.—Zeitschr. Prakt. Geol., 1898, *25*.
Bergeat, A.—Neues Jahrb. Min., B.B.28, 1909, *421*.
Bonney, T. G.—Proc. Roy. Soc., London, 1899, *223*.
Bowen, N. L.—Amer. Jour. Sci., 1915, *175*.
Brown, J. C.—Geol. Magazine, 1919, *44*.
do. —Records Geol. Survey, India, 1918, *22*.
Campbell, J. M.—Trans. Inst. Min. and Met., 1920.

Coleman, A P.—Jour. Geol., 1907, *752*.
do. —Canada, Dept. of Mines, Publ. 170, 1913.
do. —Econ. Geol., 1924, *565*.
do. —Geol. Mag., 1926, *108*.
Collins, W. H.—Canada, Geol. Survey, Mem. 95, 1917.
Cotton, L. A.—Proc. Linn. Soc., New S. Wales, 1910, *733*.
Daly, R. A —Geology of the Kiruna District, 5; Stockholm, 1910.
Daubrée, A.—Etudes synthetiques de geol. experimentale; Paris, 1870
Davison, E. H.—Mining Magazine, 1924, *15*.
Dickson, C. W.—Trans. Amer. Inst. Min. Eng., 1903, *3*.
Draper, D.—Trans. Geol. Soc. S. Africa, 1920, *43*.
Du Toit, A. L.—Cape of Good Hope, Geol. Comm., 11 Ann. Rep., 1906, *135*.
do. —(Natal) Trans. Geol. Soc. S. Africa, 1918, *53*.
do. —(Insizwa) Cape of Good Hope, Geol. Comm., 15 Ann. Rep., 1911.
Finlayson, A.—Geol. Magazine, 1910, *19*.
Foye, W. G.—Economic Geology, 1916, *662*.
Geijer, P.—Geology of the Kiruna District, *2*; Stockholm, 1910.
Gillman, F.—Trans. Inst. Min. and Met., 1896, *159*.
Goldschmidt, V. M.—Videnskaps Selskabets Skrifter, 1912, no. 22.
Gregory, J. W.—Trans. Faraday Soc., 1925, *414*.
Hall, A. L.—S. Africa, Geol. Survey, Mem. 15, 1920.
do. and Humphrey, W. A.—Trans. Geol. Soc. S. Africa, 1908, *69*.
Harker, A.—Quart. Jour. Geol. Soc., 1894, *311*.
Helmhacker, R.—Zeit. Prakt. Geol., 1893, *87*.
Hess, F. L.—U.S. Geol. Survey, Bull. 380.
Högbom, A. G.—Geol. Fören. Förhandlingar, 1898, *115*.
Holland, T. H.—India, Mem. Geol. Survey, vol. 30, pt. 3, 1901.
Howe, E.—Economic Geology, 1914, *503*.
Jones, W. R.—Trans. Inst. Min. Met., 1920.
do. —Geol. Mag., 1916, *255*.
Kemp, J. F.—(Adirondacks) U.S. Geol. Survey, Ann. Rep., 1898, *383*.
do. —(Contact deposits) Econ. Geology, 1907, *13*.
do. —(Pegmatites) Econ. Geology, 1924, *697*.
King, C.—Systematic Geology, 1878.
Knight, C. W.—Eng. and Min. Journal, 1916, *811*.
Kynaston, H. and Mellor, E. T.—S. Africa, Geol. Survey, Mem. 4, 1909.
Lacroix, A.—Carte geol. de la France, Bull. no. 71, 1900, *9*.
Lindgren, W.—Trans. Amer. Inst. Min. Eng., 1904.
do. —U.S. Geol. Survey, Prof. Paper 43, 1905.
MacAlister, D. A.—Gt. Britain, Geol. Survey (Geol. of Falmouth), 1906; (Geol. of Bodmin and St. Austell), 1909.
do. —Economic Geology, 1908, *363*.
Merensky, H.—Trans. Geol. Soc. S. Africa, 1908, *30*.
Miller, W. J.—Bull. Geol. Soc., America, 1919. *93*.
Morozewicz, J.—Tschermak's Min. Pet. Mitth., 1898.
Pettersen, W. and Sjögren, H.—Geol. Fören Förhandl., 1893, *45*.
Phemister, T. C.—Bull. Inst. Min. Met., 1924.
Poitevin, E.—Canada, Geol. Survey, Sum. Rep., 1923, A, *84*.
Prescott, B.—Economic Geology, 1908.
Reid, A. M.—Tasmania, Geol. Survey, Bull. 32, 1921.

Reid, C. and Flett, J. S.—Gt. Britain, Mem. Geol. Survey (Land's End), 1907.
Roberts, H. M. and Longyear, R. D.—Trans. Am. Inst. Min. Eng., 1918, *56*.
Rogers, A. W.—Proc. Geol. Soc. S. Africa, 1916, XXI.
Rumbold, W. R.—Economic Geology, 1909.
Scrivenor, J. B.—Quart. Jour. Geol. Soc., 1914, *363*.
Spurr, J. E.—U.S. Geol. Survey, Prof. Paper 55, 1906.
Spurr, J. E. and Garrey, G. H.—U.S. Geol. Survey, Bull. 260.
Spurr, J. E.; Garrey, G. H.; Fenner, C. L.—Econ. Geol., 1912, *444*.
Steinmann, G.—Zeit. deutsch. Geol., Gesell., 1907.
Stelzner, A. W.—Zeit. deutsch. Geol., Gesell., 1907.
Stützer, O.—(S.W. Africa) Metall. und Erz, 1914, *200*.
do. —(Yukon) Zeit. prakt. Geol., 1909, *116*.
Sullivan, E. C.—Econ. Geol., 1908, *750*.
Tchernichev, T.—Russia, Bull. Com. Geol., no. 5, 1889, *128*.
Tolman, C. F. and Rogers, A. F.—Leland Stanford Univ. Publications, 1916.
Twelvetrees, W. H. and Ward, L. K.—Tasmania, Geol. Survey, Bull. 8, 1910.
Ussing, N. V.—Denmark, Geol. Undersökning, no. 12, *97*.
Vogt, J. H. L.—Videnskaps Selskabets Skrifter, no. 1, 1918.
do. —Zeit. prakt. Geol., 1893, 1894, 1900, 1901.
Von Fircks, W.—Zeit. deutsch Geol., Gesell., 1899.
Wagner, P. A.—The Diamond Fields of S. Africa, Johannesburg, 1914
do. —(Platinum) Trans. Geol. Soc. S. Africa, 1925, *1, 83*.
do. —(do.) Economic Geology, 1926, *109, 243*.
do. —(Chromite) S. African Jour. Sci., 1923, 223.
do. —(Sulphides) S. Africa, Geol. Survey, Mem. 21, 1924.
Wandke, A. and Hoffman, R.—Econ. Geology, 1924, *169*.
Warren, C. H. and Palache, C.—Bull. Geol. Soc. Amer., 1910, *784*.
Waterhouse, L. L.—Tasmania, Geol. Survey, Bull. 21, 1916.
Williams, G. F.—Science in S. Africa; Cape Town, 1905.
Wright, C. W.—Economic Geology, 1908.
Wright, F. E. and Larsen, E. S.—Amer. Jour. Sci., 1909, *421*.
Yakowlew, N.—Verhandl. Kaiserl. Russ. Min. Gesells., 1910, *137*.
Zealley, A. E. V.—Trans. Geol. Soc. S. Africa, 1914, *60*.

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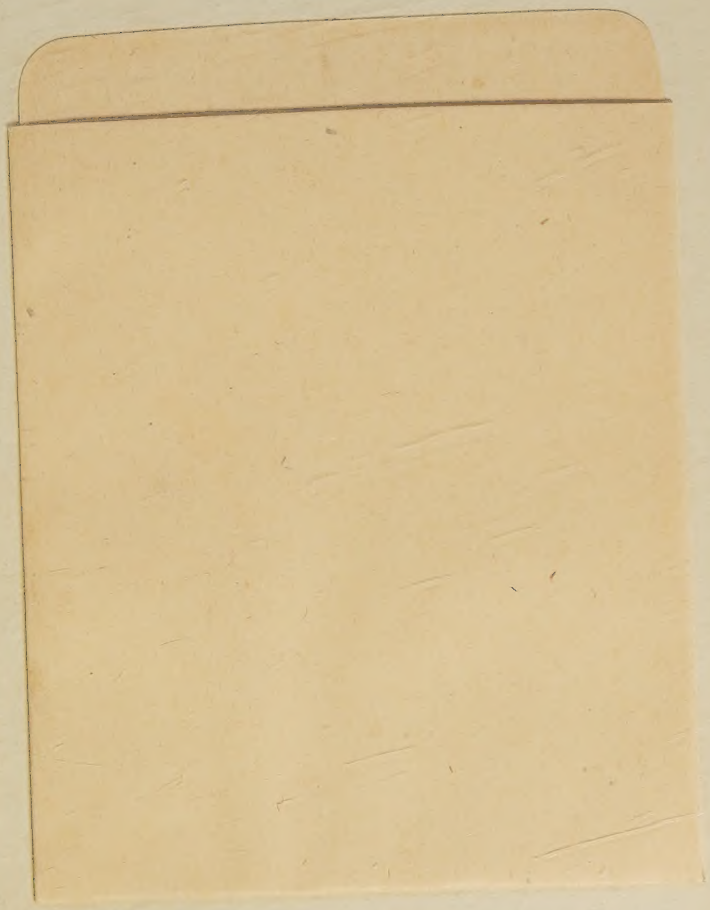

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